Essays in Sustainable Finance

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The Faculty of Business, Economics and Informatics of the University of Zurich hereby authorizes the printing of this dissertation, without indicating an opinion of the views expressed in this work.

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Zurich, September 2019

Contents

Part I

Preface and Introduction

Abstract

Four chapters form the corpus of this cumulative dissertation. The first one introduces and integrates the whole piece, while the other three are standalone essays on different areas of Sustainable Finance that rely on Real Options to asses their specific cases. This approach allowed to determine not only whether the investments should be performed, but also the optimal timing to do so.

In the first essay, entitled, "Long-Term Choices for Quinoa Farmers in Puno, Peru: A Real Options Case Study," published in the International Journal of Food and Agricultural Economics (IJFAEC) Vol. 6 No. 4 in October 2018. The goal of this article was to assess the optimal choices of a smallholder quinoa farmer in the Puno region of Peru, in terms of his decision if and when to undertake certain investments that are expected to increase quinoa yield and crop resistance to harsh weather conditions, such as frost.

In the second essay, entitled, "What are you waiting to invest? Long-term investment in grid-connected residential solar energy in California. A real options analysis." A working paper submitted to Renewable & Sustainable Energy Reviews in 2019, aims to assess the optimal choice of a household in California, United States, in terms of their decision if and when to undertake a certain investment in a residential scale, grid-connected, solar photo voltaic system, in order to obtain savings in their monthly expenditures in electricity.

The third essay: "End of Life decommissioning and recycling of Solar Panels in the United States. A real options analysis." Establishes the ground for dealing with solar panel decommissioning and recycling at the end of their useful life in the United States. This is, in fact, a very novel topic, and it is expected to be a relevant issue starting in the next decade. This paper anticipates when and where this waste is going to be produced in order to determine the optimal establishment of regional or national recycling centers to better deal with this issue in the United States.

Chapter 1

Introduction

"Climate change is the defining issue of our time and we are at a defining moment."

Secretary-General of the United Nations, 10 September 2018.

I will start work with an introductory chapter, divided into four distinct sections in order to establish the grounds of my work. In further detail, in the first section, the topic of sustainable finance is introduced, which is the general framework in which this work is set. The second section aims to introduce the context of Real Options, the methodology applied in this work. The third section provides a brief review of the literature used further in this work, and relates the three essays that form the main corpus of this work to their contribution to the body of knowledge, the first one on development finance, the second in renewable energy investments and the third in solar panel recycling. Finally, in the appendix, I introduce myself as the author of this work and narrate my motivation to start working on this field.

1.1 General framework: Sustainable Finance

Sustainable Finance is a very interesting and complex topic. Some people believe that Sustainable Finance is a new topic, but as described by Weber and Feltmate (2016) and others it is real origin can be tracked backed to the 16th century when Italian banks constructed their business on religious ethics to finance local businesses. More recent background for this field emerges in the 1970s with the grounding of ethical banks and it is followed by early stages of ESG approaches in the 1980s. But it is not until the 1990’s that Sustainable Finance is more established as a term and some other subfields such as carbon finance and impact investment start to emerge. Nevertheless, it is not until 2008, at the advent of the Financial Crisis, when assets in the United States and also all around the world suddenly lose a large part of their nominal value that this topic started to set a new understanding of the Financial Industry. The main purpose of this first chapter is to provide general elements for the reader to become familiar with this topic. The time-line in figure 1.1 below, summarizes the evolution of Sustainable Finance between the 16th and 21st centuries.

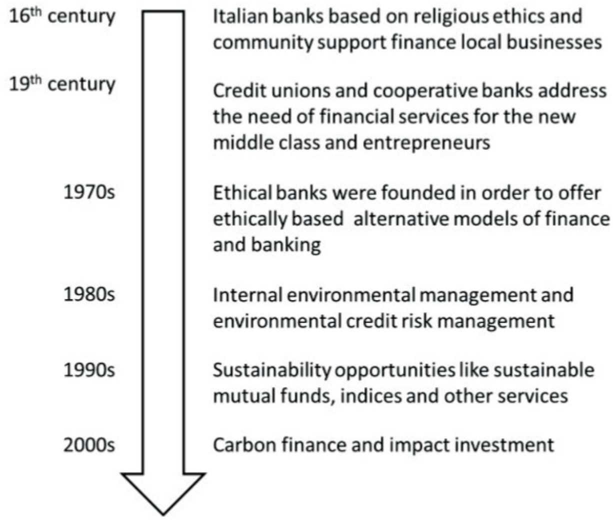

Figure 1.1: Sustinable Finance Time-line
(Weber and Feltmate, 2016)

We can also mention that there have been more concrete efforts or initiatives that grownded since 1992. UNEP-FI, the United Nations Environment Programme, Finance Initiative, established in 1992, that has been defined as a partnership between the United Nations Environment and the global financial sector. They have a mission to promote sustainable finance and have over 230 financial institutions as members. In their own word’s they ”work with UN Environment to understand todays environmental, social and governance challenges, why they matter to finance, and how to actively participate in addressing them.”[1] The Equator Principles, established in 2003, was also a relevant effort in a similar direction. It was set as a risk management framework for financial institutions. They aimed to determine, assessing and managing environmental and social risk in project finance, and provided a mini-

[1]See: www.unepfi.org for further reference.

mum standard for due diligence to support responsible risk decision-making.[2] The Principles of Responsible Investment or PRI were founded in 2006, with the aim to understand the investment implications of environmental, social and governance (ESG criteria). They went a bit further by establishing a support network for its international signatories to promote the incorporation of ESG criteria into investment and ownership decisions.[3] The Global Impact Investing Network or GIIN, founded a year after, works to reduce barriers to impact investment. They develop and provide infrastructure and developing activities, education, and research in the aim to accelerate the development of a coherent impact investing industry.[4] And several others have followed, i.e. The Global Alliance for Banking on Values (GABV) in 2008, among athers. As it can be noticed, these actors in the Sustainable Finance field have aimed to establish networks and a support system, but also have developed additional new concepts to further define the scope of this field, i.e. Impact Investment.

Sustainable finance as a subject for academic study is perhaps a bit more novel. This discipline includes economic, environmental and social factors as building blocks, and sometimes also included and touched other academic subfields, i.e. Corporate Social Responsibility, Ethics, and even Governance. This subject is just recently taught at University level, but now it is possible to find Master Programs that offer majors and minors on Sustainable Finance, however, the scope and even the literature and research that exists in this discipline although it continues to grow, it is still limited. Sustainable finance, however, has gained relevance at an accelerated pace due to the need to adapt to complex global conditions and the interest of governments, companies, organizations, and individuals in relation to sustainability.

Climate Change has also been a cornerstone of this field. The notion of Climate Change that began a couple of decades ago as a topic of debate and controversy is now a determining factor for many industries and is becoming increasingly difficult to ignore. Hundred year storms happening almost every year lead us to provide climate risks that historically we were not ready to face. Even the Dow Jones has a sustainability index now. Different actors in the financial world have started to offer services and products that can be regarded as Sustainable at different degrees. This offer responds to the interest of investors, who see that these issues have begun to transcend the concept of the trend to become the new corporate standard. Virtually

[2] See: equator-principles.com for further reference.
[3] See: www.unpri.org for further reference.
[4] See: thegiin.org for further detail.

all financial institutions around the globe now cater to investment options that include sustainability as investment criteria. These and many other examples involve the environment of Sustainable Finance.

Sustainable finance is as a holistic conception of the study of return based on risk does not ignore the traditional concepts of valuation and resource management of traditional finance, but complements and updates those concepts incorporating valuation measures of environmental and social aspects, the hand of measurement and mitigation strategies of their risk counterparts. Methodologies such as the Hedonic Valuation, Cost Benefit Analysis or Payment for Environmental Services allow establishing new parameters for a better-valued and efficient real estate industry. Thousands of companies worldwide use these and many other valuation methodologies to capture value in their investments.

All over the world, sustainable finance finds a unique moment that will allow it to advance. On the one hand, the great diversity that prevails due to globalization, both socially and environmentally, demands more and more creative conceptions of companies and projects that promote the development of communities and capture the added value in them. The interest in organic products, handmade production, the increasingly numerous socially responsible companies and the rescue of the traditional are only part of this. But on the other hand, the growing interest in Fintech driven by a global trend and supported by markets, in conjunction with an energy reform that finally cracks the state's electricity production monopoly and begins to explore new schemes of renewable energy production they flatten the road to the use and study of Sustainable Finance.

But what is sustainable finance? This a question that has arised now for sometime, and we can then say that there is no easy answer. The most commonly accepted definition is the one that states that Sustainable Finance comprises the integration of environmental, social and governance (ESG) criteria into value assessment and risk management. Other go beyond and establish that Sustainable Financial contributes to sustainable development and value creation in economic, environmental and social terms. In other words, one that ensures and improves economic efficiency, prosperity, and economic competitiveness both today and in the long-term, while contributing to protecting and restoring ecological systems, and enhancing cultural diversity and social well-being.[5] As we can observe Environmental, Social and Eco-

[5]Swiss Sustainable Finance, 2019. For further reference, see: http://www.sustainablefinance.ch/en/what-is-sustainable-finance-_content---1--1055.html

nomic terms seem to be the common fabric, but their interpretation and assessment cannot be easily defined either.

And there are also some generally agreed upon activities that fall under Sustainable Finance, i.e. renewable energy, development, green bonds, impact investing, microfinance, green real estate, etc. This work mainly contributes to the study of the first two activities listed above. Perhaps then, the ESG component, or as some others call it, impact, could be the differential component between sustainable finance, and convention finance. Nevertheless, what about charity and philanthropy, which aim to have social and sometimes environmental impact. Weber proposes an interesting diagram to establish how this could be determined in Figure 1.2.

Figure 1.2: The Sustinable Finance hue
(Weber and Feltmate, 2016)

Specifically for Impact Investment, which is an area of Sustainable Finance we can also observe another stylized representation where we appreciate, now in two dimensions how both financial return and impact are aimed. A good sustainable finance product would actually target both goals, and would not determine a trade-off between them. Traditional finance in the meanwhile would always forgo impact in the aim of traditional return, while philanthropy would prioritize return over its intended impact mandate. This is fact contradicts the conception of Freedman, who in 1970 published an essay on The New York Times Magazine entitled "The Social Responsibility of Business is to Increase its Profits"[6] and the piece delivered well for its title. In his own view, "social responsibility" to the public or society for corporations is limited to increasing profits for for its shareholders. That was the traditional view of finance embedded in regulation for decades to follow, and currently challenged by Sustainable Finance. The conception of Impact Investment as "a powerful instrument of change" (Rodin and Brandenburg, 2014) comes later in 2014 with the support of the Rockefeller Foundation among others open the possibility for aiming

[6]For further reference see: http://umich.edu/~thecore/doc/Friedman.pdf

to maximize financial return and impact, without tradeoffs, as shown in figure 1.3

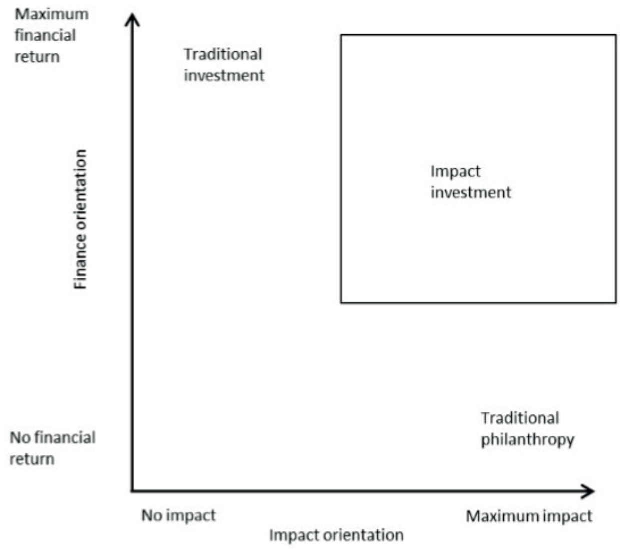

Figure 1.3: Impact Investment according to Finance and Impact orientation (Weber and Feltmate, 2016)

Thematically, most financial institutions focus their efforts in areas such as Microfinance, Renewable Energy and Rest State (or housing mortgages) but other aspects of it, such as Agriculture, Arts and Culture, Health-care, Community development, and Education, among others Weber and Feltmate (2016). And assets under management for this sort of investments register important growth in recent years, i.e. reaching over 3,500 Billion USD in 2012 acoording to Weber and Feltmate (2016)

Valuation methodologies vary by geography, but regardless of its limitations Time Value of Money continues to be the most popular technique to asses benefit, although some more complete and complex techniques have been developed to deal with Environmental and Social value in particular, but also with Sustainable Value as a holistic concept, i.e. Contingent Valuation, Hedonic Valuation, Carrying Capacity, Cost Benefit Analysis, Life Cycle Assessment and Costing, Vulnerability and Resilience Assessment, among others. Each one of these techniques poses particular advantages and disadvantages depending on data availability and valuation scope, but in most cases tend to static methodologies. Real Options Assessment, stands out as one valuation methodology that performs a dynamic assessment of value, and this work aims to provide the application of this methodology to Sustainable Finance.

1.2 Methodology: Real Options

Real Options are the right, but not the obligation to undertake a certain investment action. This could mean deferring, abandoning, expanding, staging, or contracting an investment project. A typical example could be any of the cases described in the present work. i.e. to implement new technology or change choose a better crop to grow, invest in a renewable energy project or a solar panel recycling facility. Real Options Assessment or ROA is an analogy to financial options. Seminal work on this field can be found in the book "Investment under Uncertainty" by Dixit et al. (1994), and later in other work by other authors including Jeanblanc et al. (2009).

Traditional literature differentiates several types of real options, as shown below. This work deals with the former three types listed, provided the latter two imply reversibility and that was not a consideration within the scope of this work.

- The option to postpone or defer the investment in order to obtain information or to await technological development. i.e. In the case of residential grid connected solar PV investments in California, shown in Chapter 3 of this work. This option could also be described as a timing option.

- The option to change the size or segment an investment to minimize risks or redistribute cost. This option would aim to break down the investment, thus enabling flexibility, i.e. in the case of recycling centers for solar PV panels in the United States, shown in Chapter 4 of this work.

- The option to change inputs/outputs. This option refers to an ability to change input materials or fuels or output products. A good example would be the case of Quinoa farmers in Puno Peru shown in Chapter 2 of this work.

- The option to abandon the invest in case necessary, by stopping or selling the project.

- The option to restart the project. This option provides flexibility to adapt to changing demand or other conditions, and deals with the assumption of irreversibility.

ROA is regarded as a dynamic valuation methodology, and offer significant advantages to more traditional valuation methods, i.e. Time Value of Money, also known as TVM, which is, in fact, a static valuation methodology and so does not provide decision making support under uncertain circumstances. ROA on the other hand is well suited to estimate investments with uncertain cost, interest rates, or else. Investment decisions assessed on ROA are typically considered to be irreversible, provided financial or practical implications of implementation, and further work has been developed by some authors to overcome this assumption, however, all three chapters of this work comply to the irresistibility assumption provided their particular characteristics. Further detail on the applications of ROA in each specific case can be found in this work. As a literature review regarding renewable energy, recycling and agricultural investments can also be found in the literature section of each chapter.

1.3 Literature review and contributions of this work

Since detailed bibliography for all cases presented ahead is offered on each the essays presented I wanted to take this opportunity to introduce the general body of knowledge that frames this work in order to provide context of our contribution.

For the first essay, "Long-Term Choices for Quinoa Farmers in Puno, Peru: A Real Options Case Study,"[7] We contributes to the existing literature by developing a dynamic real options model that accounts for market and environmental dimensions of quinoa agriculture in Peru. We recognize that the concept of option value is not new to this field, and in fact has been recognized in environmental economics since several decades, even before the appearance of real options (Arrow and Fisher, 1974; Fisher and Krutilla, 1975; Henry, 1974), but we offer an assessment that is innovative for both quinoa and Peru. Real Option Assessment in any case is not foreign to Latin America. Numerous studies have been developed to describe different issues within the region, i.e. an application of ROA in Peru is done by Chesney et al. (2017), whereby the authors focus on REDD (Reducing Emissions from Deforestation and Forest Degradation) projects and aim to identify the optimal deforestation rate and timing to enter the REDD scheme under different risk aversion scenarios. However, the application of this methodology to agriculture in Latin America, and in particular to Peru, is quite novel.

In the second essay, entitled, "What are you waiting to invest? Long-term investment in grid-connected residential solar energy in California. A real options analy-

[7] With Anca Balietti and Prod. Dr. Marc Chesney. Published in the International Journal of Food and Agricultural Economics (IJFAEC) Vol. 6 No. 4 in October 2018.

sis."[8] The general setting of this paper is based on the work of Bauner and Crago (2015); Chesney et al. (2017) and establishes the benchmark of a typical household with an investment irreversible option to install a solar PV system. Although Bauner and Crago (2015) present an application only for the state of Massachusetts, their model of adoption of residential solar power under uncertainty is quite relevant to the scope of this work. Our model examines the current dynamic of residential grid connected PV systems in California from the perspective of the household. We assume that the decision maker knows investment amount but has uncertainty about potential savings in order to make an optimal decision, in terms of investment timing.

The third essay: "End of Life decommissioning and recycling of Solar Panels in the United States. A real options analysis."[9] Establishes the ground for dealing with solar panel decommissioning and recycling at the end of their useful life in the United States. This is, in fact, a very novel topic, and it is expected to be a relevant issue starting in the next decade. This paper anticipates when and where this waste is going to be produced in order to determine the optimal establishment of regional or national recycling centers to better deal with this issue in the United States. With this work we contribute to the existing literature by presenting a model that estimates the viability of distinct potential solutions for the PV recycling problem in the United States, accounting the uncertain timing of the life-cycle of PV panels and provided multiple market factors. The value added of this paper is that it assesses the problem of PV recycling in the United States before it becomes a problematic situation resulting in hundreds of thousands of scrap to be improperly disposed of. This model also deals with real options regarding the optimal location which is a novel approach. The financing gap that could result from the imminent interest in solar PV recycling could also result in a financing gap, such as the one that currently exists in solar PV investments and energy storage. Further research would be needed in that regard. Finally, research comparing different solar PV markets, i.e. the United States and Europe is also common, for an example, we can see Seel et al. (2014). Further work on recycling could also be done not only including those two markets, and China, India and other global players as presented by different authors (Chi et al., 2014; **?**; Lee and Shih, 2010; Ding et al., 2016; Weckend et al., 2016).

As it can be observed further in this work, other Real Options Analysis work can

[8]Working paper at the University of Zurich with Prod. Dr. Marc Chesney, submitted to Renewable & Sustainable Energy Reviews in 2019.

[9]Working paper at the University of Zurich with Prod. Dr. Marc Chesney.

be found in the field of climate change that could also be extrapolated to energy modeling. Chesney et al. (2017) elaborate on more on this by introducing risk aversion in Real Options while assessing the optimal choices of a forest owner given his option to enter an irreversible scheme that provides uncertain cash flows under different risk aversion scenarios. Considerations of game theory and competition could also be included to asses competition once the market matures, and new entrants start to interest in this market, and such situation could by captured by a model such as the one proposed by Botteron et al. (2003). Besides the entry barriers already highlighted, intermittent production is the other key challenge to solve. Also, the model proposed by Rai and Robinson (2015) incorporates the integration of social, behavioral, economic, and environmental factors in a model of energy technology adoption. This could also be good to include in further research.

The findings of this work will help better understand the applications of Real Options Analysis in the field of Sustainable Finance. Considering that this is a very rich and diverse field it was relevant to include cases that touched on different areas, i.e. agriculture, renewable energy and recycling.

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Appendix

About the author

I am Carlos Vargas, born in Texas, in the southern part of the United States. I was the youngest of thirteen siblings. I grew up in the city of Guadalajara in the western part of Mexico, where I lived most of my life. I have also lived in many other places, including Los Angeles, Boston, Calgary, Madrid, and Berlin, mainly driven by professional and academic aspiration. I'm currently living in a Zurich, as I am finishing my doctoral degree at the University of Zurich, precisely in sustainable finance because it's a subject that I have found to love through years of research and practical work. I have been teaching Sustainable Finance and Investments for over seven years, in Summer and Extension Schools at Harvard University. My research experience is mostly in Development Finance and Renewable Energy. I also have relevant experience on the field from the practitioner side where most of my experience came from Investment Banking, Corporate Finance, and Project Valuation.

Multidisciplinarity has enriched my research and professional approach and this is shown in this work. My experience in Sustainable Finance is vast, but it is also very heterogeneous. As for my academic background, I hold a BA in Finance, an MBA, and an MLA in Sustainability and Environmental Management. I have lectured, Sustainable Finance and Investments and Environmental Economics, at Harvard University, for the last 7 years. I have guest lectured in several universities in Mexico, Switzerland, and the U.S.

Beyond the scope of this work, my research interest for the near future can be divided into two parts. The first part is centered in Sustainable Finance, mostly focused on quantitative analysis of value creation through sustainability, in order to better serve investors and make Sustainable Finance mainstream in global markets and particularly for Europe and Latin America. This includes, for example, the development of further applications of Real Options Analysis, which has been the core of my Ph.D. work. For the second part of my research, I anticipate to include some multidisciplinary elements in my research, i.e. social impact, corporate governance, behavioral finance, prevention of child labor, ESG analysis, impact investment in culture, among other topics in order to enrich my knowledge.

Part II

Research Papers

Chapter 2

Long-Term Investment Choices for Quinoa Farmers in Puno, Peru: A Real Options Case Study.

with Anca Balietti and Marc Chesney

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Abstract

The aim of this article is to assess the optimal choices of a smallholder quinoa farmer in the Puno Peru, in terms of their decision if and when to undertake certain investments that are expected to increase quinoa yield and crop resistance to harsh weather conditions, i.e. frost. We focus on two options, namely quinoa variety management and Waru Waru. The former alternative considers the option of the farmer to switch from his business-as-usual quinoa variety to one that has different yield and frost resistance characteristics. The latter alternative refers to the implementation of an ancestral cultivation practice that is estimated to offer benefits in terms of yield increase and resistance to harsh climate conditions. We rely on Real Options Analysis to assess these opportunities for the farmer. The article also discusses how quinoa price dynamics, yield sensitivity to frost, and governmental support impact the decisions of the smallholder farmer Keywords: Quinoa; Smallholder farmers; Real Options; Price and weather uncertainty; Waru waru; Food security; Latin America.

2.1 Introduction

Food security is one of the main topics on the international development agenda and plays an important role in the achievement of the first two United Nation's Sustainable Development Goals UN (2015). Food security is concerned not only with the capacity to produce enough food to feed the world population, but also with the way production is achieved.

Around the world, meat protein is massively grown for human consumption. However, the amount of resources used in the process has significant environmental impacts, including climate change. In this setting, quinoa stands out as an interesting alternative to efficiently produce protein for human consumption, as recently globally popularized by FAO (Ruales and Nair, 1992). However, quinoa production has historically prevailed in localized areas of Peru, Bolivia, and Ecuador, and it remains debatable whether massive global production is a viable and sustainable option. In fact, the introduction of quinoa on international markets has been challenging for the local producers, being termed "the food sovereign paradigm" (Avitabile, 2015).

Quinoa is mostly produced as a subsistence crop by local farmers in Latin America. Thus, a thorough assessment of quinoa production should consider not only price dynamics and weather processes, but also the possibility of increasing overall production in a steady and sustainable way. The International Year of Quinoa in 2013 proved the potential size of the global demand for quinoa; however, the sharp and sustained drop in prices observed in the years following the event also proved the great threat local producers face when linked to global markets; see Figure 2.1.

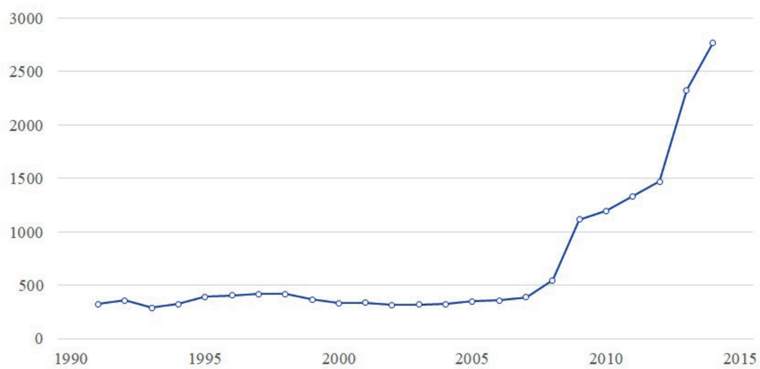

Figure 2.1: Official Price of Quinoa in USD per Hectare as reported by FAO FAO (2017)

This article aims to evaluate two important decisions available for a smallholder quinoa farmer. We focus on two irreversible options, namely quinoa variety management and Waru Waru. The former alternative considers the option of the farmer to switch from his business-as-usual quinoa variety to one that has different yield and frost resistance characteristics. The latter alternative refers to the implementation of a traditional cultivation practice that is estimated to offer benefits in terms of yield increase and resistance to harsh climate conditions.

Our study relies on a Real Options Assessment (ROA) model applied from the perspective of a representative smallholder quinoa farmer. The RAO approach is especially useful for taking decisions under uncertainty. In finance, an option is a title that gives its owner the right, but not the obligation, to buy (in the case of a call option) or to sell (in the case of a put option) another financial title, such as a stock. After the option is exercised (if that becomes optimal ever), there is no return to the previous situation. A real option involves a similar decision, except that the approach is applied to a real life decision rather than to a financial instrument (Chesney et al., 2017b). In the context of this article, the representative farmer may choose to invest in a technology that improves the quinoa yield; here, exercising the option means investing in such technology by spending resources to that end; once the investment has been made, the decision is considered irreversible. Moreover, the ROA allows not only for the identification of the decision whether or not to invest, but it helps determine also the optimal time to exercise the option.

Real option models are particularly well-adapted in the context of optimal stopping time problems. They are used in order to check whether decisions should be taken or postponed. The standard tool used in this setting is the Net Present Value (NPV) analysis; however, we decided to use a more flexible tool in order to consider delays in the investment, namely ROA. According to this methodology, an investment should be realized if and only if its NPV, i.e. the difference between its expected discounted payoffs and costs, is positive. The criteria for NPV is then static to the extent to which the choice is between realizing the investment at the date when the NPV is calculated, or never. This is a significant drawback of the NPV criterion. If, instead, investment opportunities are considered as real options, the investor has the right, and not the obligation, to make an investment during a given period of time. When identifying the optimal investment decision, the possibility of postponing the investment is also taken into account. ROA accounts for the fact that performing an irreversible action at one point in time involves the cost of renouncing the flexibility to wait; if this cost is correctly taken into account in a cost benefit analysis, in order for the action to be economically justified, the benefits from the decision must be higher than in a traditional cost benefit analysis (Chesney et al., 2017a).

We employ the ROA approach and calibrate our model to the best available information characteristic for the Arapa District (Puno, Peru). We find that one quinoa variety (Kancolla) offers the highest benefits to the farmer and switching to this option should be immediate if investment costs are low; however, as costs increase, the decision to switch quinoa variety is optimally postponed until quinoa price uncertainty is reduced. We find that the Waru Waru option is not worth undertaking unless further evidence related to the increase in the productivity of quinoa is developed. However, at increases in productivity above 20%, the Waru Waru option becomes highly attractive. The article also discusses how quinoa price dynamics, yield sensitivity to frost, and governmental support impact decisions.

2.2 The setting of quinoa farming in Peru

2.2.1 Quinoa

Quinoa or "quinua"is the generic name for Chenopodium Quinoa, a crop from the family of the amaranth. It is commonly believed that quinoa is a grain; however, from a botanical perspective, quinoa is a relative of spinach, beets and chard (FAO, 2013a). The main world producers of quinoa are Bolivia and Peru. In 2008, the two countries accounted for 92% of the world quinoa production (FAO, 2015).

Traditionally, quinoa has been cultivated in a very rudimentary and organic fashion, since it was first domesticated by the indigenous population in the Andean region around 7,000 years ago (FAO, 2015). The most popular variety of quinoa worldwide is the white type, produced mainly in the "Sierra" or mountain range of Peru and Bolivia. White quinoa tends to grow in semi-dry areas and is produced in a traditional fashion that usually does not require the use of pesticides. However, most of this production is sold at market price and does not capture the potential benefit of organic certification price premiums.

Depending on the region where the crop is cultivated, there are five general types of quinoa[1] (FAO, 2013b): (i) dry valley and humid valley, (ii) altiplano (white and colored), (iii) saltflat, (iv) sea level, and (v) the Yunga agroecological zone and sub-

[1]This five general Quinoa types are not to be confused to the specific seed varieties described in the Section "Longterm investment options in quinoa" of this article.

tropics. Only the first two varieties are cultivated in Peru, while the third and fifth varieties are attributed to Bolivia, while the sea level variety is better adapted to Chile.

This Andean endemic crop is recognized to have important nutritional properties and to have the potential to become an important part of global agriculture, as a main source of protein or a "Super Food." In fact, the year 2013 was declared by the United Nations "The International Year of Quinoa" or "IYQ"(FAO, 2013a). This acknowledgment helped to draw the world's attention to the role that quinoa could play in providing food security, nutrition and poverty eradication in support of achieving Sustainable Development Goals. The IYQ also allowed for quinoa prices and production to flourish experiencing an atypical increase of between 2012 and 2014 according to official sources. In fact, producer prices increased 139% during the period, while area harvested followed with a corresponding increase of almost 175% (FAO, 2017); see Figure 2.1.

A crop with high nutritional value, quinoa has historically played an important role for low-income inhabitants in Peru and the Andean region in general. In the recent past, quinoa has become a crop of international importance for people at all income levels and, as a consequence, its production has increased considerably. The trend is expected to continue; Furche et al. (2013) estimate an average annual growth of 22.8% in production for the 1992 - 2012 period.

The increase in quinoa production does not come without environmental side-effects. Jacobsen (2011) warns about the rapid degradation of natural resources due to unsustainable land use for quinoa farming in Bolivia. The observation has been contested in later studies; Winkel et al. (2012) stress that there is no sufficient scientific evidence regarding the rapid social and environmental dynamics in the region, and claim that the report of Jacobsen (2011) misrepresents the situation of quinoa production in southern Bolivia. Data availability for the analysis of social, environmental, and even economic issue in the region remains limited at best.

2.2.2 The study location: Puno

This study focuses on quinoa smallholder farmers in Puno, one of the 24 departments of Peru, formed by 13 provinces in the southeastern area of the country. Puno is located in the western part of the Lake Titicaca, over the Collao Plateau. The Andean mountains make up to 70% of the department's area, and the rest is covered by part of the Amazon rainforest. There are two very distinct regions in the Department of Puno: the plateau or "Altiplano" and the mountain region or "Sierra". Both areas have a cold and dry climate, with a three-to-four month long rain seasons, and a couple months of a very dry season, usually in June and July.

As Puno is located in high altitude, it experiences more extreme meteorological conditions than the rest of the country. Soil characteristics tend to be arid or semiarid. Although water is available near the lake area, it is a limiting factor in most of the region. Puno has also been regarded as the cradle of domesticated potato agriculture and is currently is the main producer of quinoa in Peru (Ministerio de Agricultura y Riego, 2017).

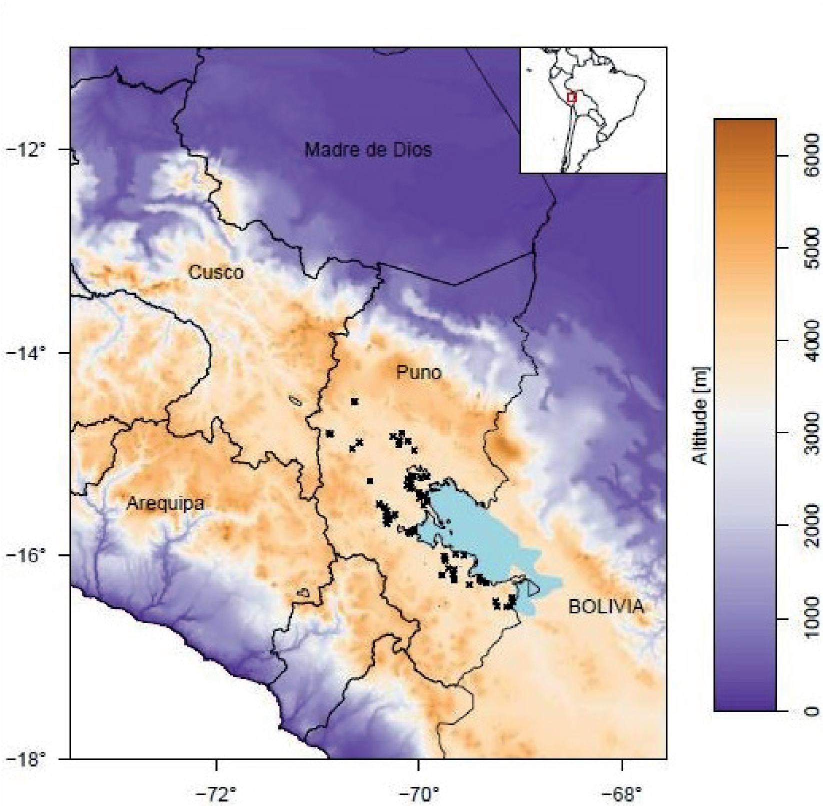

Figure 2.2: General location of weather stations in Puno
SENAMHI (2017)

According to information provided by SENAMHI[2], there are 44 weather stations located in Puno. However, data from only 5 stations has been cleaned and could be used for analysis at the time of this study[3]; see Figure 2.2 for a general reference

[2]Servicio Nacional de Meterología e Hidrología del Perú.

[3]These are Desaguedero in the South, Lampa, Puno and Pampahuta in the central part, Arapa, Progreso and Chuquibambilla in the North.

on the location and altitude of the Stations in Puno. The availability of data to be inputed in our model is largely restricted and some of it is not available from local authorities, i.e. Dirección Regional Agraria (2017). Under these conditions, we restricted our analysis to Arapa, whereby both the availability and quality of the data was assessed to be higher.[4]

2.3 Literature Review

This article evaluates agriculture decisions in Latin America. Given the vast importance of this sector for the economy of the region, it is not surprizing that most academic research targeting this area focuses on agriculture. Kaufmann and Snell (1997) assesses the sensitivity of corn yield to climatic, social and economic factors. Sietz et al. (2012) identify the patterns of smallholder vulnerability to weather extremes impacting food security in the region. Altieri and Nicholls (2017) focus on the potential role of adaptation and mitigation strategies of climate change for traditional agriculture. They identify the external drivers of vulnerability, and point to the potential of Waru Waru raised fields to reduce such vulnerability. In fact, they describe Waru Waru and similar techniques as *models of climate smart traditional agriculture*. Barrera et al. (2012) study natural resource management in Ecuador and show that the implementation of enhanced management practices contribute to reduced environmental vulnerability and improved welfare.

Our article assesses two long-term investment options for quinoa farmers in Puno. We analyze at the option to switch quinoa varieties and the option to invest in the setup of a Waru Waru agricultural technique. The literature on the latter investment dates quite a while back given the long history of this agricultural approach; however, not many new assessments have been performed in the last decade to update the analysis to present times. Erickson (1986) offers a review of the literature related to raised field practices in agriculture, among which Waru Waru, and provides some information about the potential increases in quinoa yields obtained under Waru Waru compared with the business-as-usual. Mujica Barreda (1997) extends this research and offers a more comprehensive analysis on the profitability of the raised fields in Puno. He specifies the increase in profitability of Waru Waru systems when compared to equivalent fields that do not apply this technology at about 20%.

[4]Some other stations, such as Pampahuta, were regarded to be too high in elevation (over 4300 meter above sea level) and resulted to be irrelevant for the study.

Lhomme and Vacher (2003) highlight the benefits of using the raised fields approach; in particular, Waru Waru is estimated to reduce the effects of night frost. Although their study focuses only on the cultivation of potatoes, it is expected that their findings apply to quinoa as well. Llerena et al. (2004) review 19 articles that describe the physical characteristics of the raised fields in Peru and particularly account for the historical reasons behind the abandonment of these technologies. It is implied in most cases that such abandonment followed particular historic events, such as the elevated mortality in the Indian population in the pre-Columbian era. Llerena et al. (2004). However, not much is clarified regarding the reasons that explain the current low use of the technique in the Andes.

Our article contributes to the literature by developing a dynamic real options model that accounts for market and environmental dimensions of quinoa agriculture in Peru. The concept of option value was introduced in environmental economics since several decades, even before the appearance of real options (Arrow and Fisher, 1974; Fisher and Krutilla, 1975; Henry, 1974). Real Option Assessment is not foreign to Latin America. Numerous studies have been developed to describe different issues within the region; however, the application of this methodology to agriculture in Latin America, and in particular to Peru, is quite novel. Among the few contributions, an application of ROA in Peru is done by Chesney et al. (2017a), whereby the authors focus on REDD (Reducing Emissions from Deforestation and Forest Degradation) projects and aim to identify the optimal deforestation rate and timing to enter the REDD scheme under different risk aversion scenarios.

We rely on ROA to assess two long-term investment options, i.e. quinoa variety management and Waru Waru. One leading goal of the article is to highlight the relevance of relying on ROA models in agriculture. ROA accounts for the flexibility to postpone investment until part of the underlying uncertainty is resolved, offering estimates related to the optimal investment time. The methodology can also be applied to a portfolio of decisions, where several investment option are assessed simultaneously. Another contribution of our model is to incorporate stochastic weather processes into the decision-making process.

2.4 Long-term investment options in quinoa

This section provides details on the two agriculture techniques relevant for the quinoa smallholder farmer in Puno. The model to evaluate the two options and the main results are fully described in the following sections.

2.4.1 First option: Quinoa variety management

In the world, there are roughly 120 known seed varieties of Quinoa. Among them, only 13 seed varieties appear to be commercially feasible in Peru (FAO, 2015). Quinoa varieties come in a diverse palette of colors, with white being the best known globally due to the long tradition of its organic cultivation since centuries; red and black varieties are also gaining relevance on some markets. Aside from color, quinoa varieties come with different levels of yield and resistance to drought or salinity. In fact, according to the survey led by MeteoSwiss, farmers tend to have different preferences for particular quinoa varieties, depending on factors such as tradition, experience, and peer influence. Although many talk about the differences in characteristics of quinoa varieties, very little has been researched to quantify their benefits. Unfortunately, only scarce information exists with regards to differences in agrobotanical and phenological characteristics, the response to biotic and abiotic factors, or the nutritional value of commercial varieties (FAO, 2015). This gap in unfortunate, as such information could be especially useful for farmers and agricultural entrepreneurs trying to optimize their quinoa production. This is especially true given the fact that there seems to be no incremental cost in producing any specific variety of quinoa, despite the difference in yields and weather resistance.

For the purpose of this study, the management of quinoa varieties was regarded as an independent and exclusive option in which the producer has the opportunity to choose the quinoa variety that optimizes the revenue. Given the data limitations mentioned above, we lead a sensitivity analysis trying to account for a wide range of scenerios.

2.4.2 Second option: the Waru Waru technique

Waru waru is a system of soil management for irrigation purposes and weather mitigation that is believed to have been developed before the raise of the Inca empire in the year 300 B.C. (OAS, 2017). Waru Waru is a technique suitable to areas with extreme climatic conditions, such as mountainous areas that experience heavy rainfalls and periodic droughts, and where temperature fluctuations range from intense heat to frost. It is also believed to be very useful in arid and semi-arid areas, such as the Andean region of Peru and Bolivia (OAS, 2017). Despite its expected benefits, the prevalence of the technique remains low. Even more, it appears that even after implementation, Waru Waru has been abandoned in 3 out of 4 projects[5]. For the purpose of this study, Waru Waru was regarded as an independent and exclusive option.

2.4.3 Other investment options

In our study the two investment options have been regarded as independent and exclusive. One could argue that the two options should be assessed simultaneously, which could be achieved with the real options approach. However, this would require the estimation of the joint impact of the two options on the revenues of the farmer. Since such correlation has not yet been assessed for these options, the joint evaluation remains out of the scope of the present study, but it could be incorporated in a later stage of the project as information becomes available.

On the same esteem, there are further options that were not included in the current stage of this study such as organic certification, irrigation, technification, climate insurance, use of pesticides, etc. Such options could also result in significant benefits for the producers and could be assessed in a further stage of analysis. Some options, such as irrigation and technification, require that the assessment be led at the community level and not at a farmers level, which would call for a different theoretical model altogether.

Furthermore, important applications of this model could also be implemented for other regions of Peru, including Cuzco, and the costal area. The model could also be applied to obtain further findings in other countries that are also relevant for Quinoa production such as Bolivia and Ecuador. Data for Quinoa in the Andean region seems to be more available for such countries, but it was outside of the scope of this stage of the study to include them as part of it.

2.5 Model and numerical methods

This section describes the main theoretical setup of our decision-making model that will be solved with the help of the real options approach. We also dig into the main assumptions regarding key model parameters and give details on their calibration.

[5]Source: Interview with Dr. Alipio Canahua Murillo, April 2017.

2.5.1 Model setup

In this article, we take the view of a smallholder quinoa farmer in the Peruvian altiplano that is considering several investment options that could increase his overall profits. The two long-term decisions he is evaluating are (i) changes in quinoa variety and (ii) the Waru Waru farming technique, as described in Section 2.4. The two options[6] consist in very different farming options, the evaluation of their feasibility calls for a fairly similar decision process. Namely, we assume that the representative quinoa farmer is a rational decision maker who will choose to invest if and only if the investment will increase the expected sum of future discounted yearly profits compared to the business-as-usual. We assume that the investment horizon of the farmer is $[0; T]$; in our numerical solution, we consider $T = 20$ years and a discount rate of 9%.

Under the business-as-usual, where no long-term investment option has been implemented so far, the yearly profit of the farmer will be given by:

$$\pi_t^{BaU} = P_t q_t(W_t) - C(q_t) \tag{2.1}$$

Equation 2.1 describes the factors that influence the current yearly profit of the farmer, where P_t is the year t price of quinoa. q_t is the quantity the farmer harvests at the end of the planting season. As described below, we allow q_t to be a function of weather conditions (W_t). $C(.)$ is the cost production function that depends on the quantity produced that year (q_t). Without loss of generality, we assume one hectare of land; thus the quantity harvested q_t is measured in tons of quinoa per hectare.[7]

Quinoa is a highly robust crop with high tolerance for weather variations compared to other crops. However, the plantation of quinoa is not totally immune to weather conditions. In fact, the survey administered to farmers in Puno highlights that the conditions that are of highest concern for quinoa farmers are above all frost, followed by drought and hail. We thus opt here for modelling the quantity of quinoa harvested as a function of frost events, as described below.

To increase their yearly yield and reduce the vulnerability of quinoa production to weather conditions, the quinoa farmer has a set of long-term investment options

[6]Although the two options are equivalent to an investment decision, we recognize that the farmer does not necesarly fund them directly as he can get partial or complete direct fonding from third parties, i.e. the governement, NGOs, etc.

[7]The results of the survey of quinoa farmers in Puno reveals that the average plot size sowed with quinoa was of 0.47 hectares during the 2015/2016 harvest.

he can undertake. In our model, if the farmer undertakes an investment (A), his yearly profit would be modified and given by:

$$\pi_t^A = P_t q_t(W_t, A) - C(q_t, A) \tag{2.2}$$

where P_t is the time t price of quinoa, q_t is the quantity harvested depending on both weather conditions (W_t) and the long-term adaptation option that has been already implemented (A), and C is the cost production function that depends on the quantity produced and the adaptation options already implemented by the farmer.

Consider now that the farmer is evaluating the option to undertake a long-term investment in the future. The expected total revenue of the farmer is given by the sum of yearly profits under the business-as-usual and under the new regime after the investment has been made:

$$\Pi = \mathbb{E}\left[\sum_{t=0}^{\tau_A} e^{-rt}\pi_t^{BaU} - IC_{\tau_A}e^{-r\tau_A} + \sum_{t=\tau_A}^{T} e^{-rt}\pi_t^A\right] \tag{2.3}$$

where IC_{τ_A} is the one-time sunk cost the farmer incurs with the investment in option A. In Eq. 2.3, τ_A marks the time of the investment. Formally, τ_A is a stopping time, whereby the farmer moves from the business-as-usual regime to the post-investment one. Let $(\Omega, F, \{F_t\}_{t\in I}, \mathbb{P})$ be a filtered probability space, i.e. a probability space equipped with a filtration of σ-algebras. Then the random variable τ_A is a stopping time if $\{\omega \in \Omega : \tau(\omega) \leq t\} \in F_t$, i.e. the decision to stop waiting and to invest is only based on historical data.

The farmer will decide when to invest in the adaptation option by maximizing his total expected future profits:

$$\max_{\tau_A} \Pi \tag{2.4}$$

2.5.2 Assumptions regarding the model variables

The price of quinoa

One important model variable is the price of quinoa and its evolution over time. To represent the price dynamics, we rely on the historical distribution of quinoa prices received by the farmer in the Arapa region. Figure 2.3 below captures the historical quinoa price evolution.

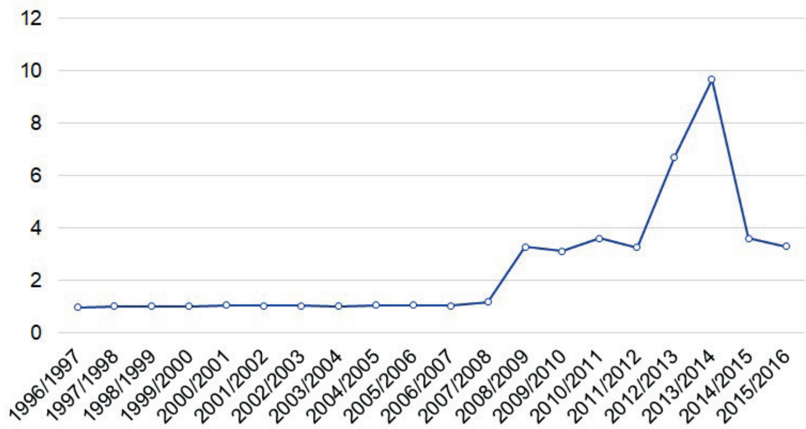

Figure 2.3: Historical evolution of the price of quinoa as received by the producer in Arapa (Puno). Source: Own illustration based on data from INEI (2017).

While for a long time quinoa prices have been stable at a low level per kilogram (until 2008), with the international increase in the demand for quinoa, prices have experienced severe shocks over the last decade.[8] Based on these historical observations, we suggest to model the quinoa price with the help of a random variable represented by a trinomial tree. Namely, each year the quinoa price received by the producer can (i) remain at the level of the previous year with probability $p_1 = 0.1579$, (ii) increase by 20.28% relative to the previous year with probability $p_2 = 0.4737$, or (iii) decrease by 28.37% percentage points relative to the previous year with probability $p_3 = 0.3684$, where all price movements and associated probabilities have been calibrated on historical data.[9]

Weather conditions impacting the harvest of quinoa

Among the weather phenomena impacting quinoa production, we choose to focus on agronomic frost (defined as temperatures at and below -4° C), as it is the event farmers seem to be mostly concerned with based on the information gathered in the individual surveys. The number of yearly occurrences of days with frost during the harvest season (September - May) can be modeled as a random independent

[8]2014 has been named the "International Year of Quinoa" and governmental support for quinoa promotion has boosted the price of quinoa to almost ten times its historical average. Prices have since fallen dramatically but fluctuate above the long-term mean.

[9]The probabilities and respective percentage moves have been estimated based on the historical distribution of the quinoa price received by the producer in Arapa. A historical price change in the range [-1%;1%] has been considered insignificant and therefore counted as a zero change in price. The percentage changes have been computed as averages of upward and downward moves.

variable. We rely on historical data to estimate the distribution of the number of frost days during the harvest season. Fig. 2.4 below captures the evolution of frost days in a harvest year in Arapa (Puno).

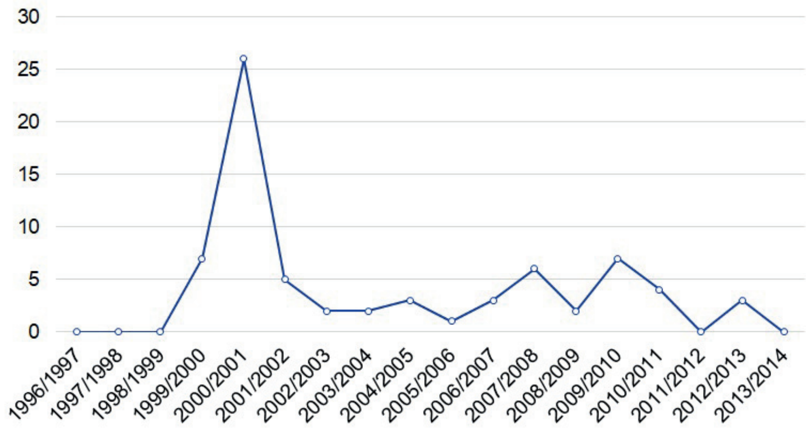

Figure 2.4: Historical evolution of the number of frost days in Arapa. Source: Own illustration based on data from SENAMHI (2017)

The historical frequency of the number of frost days impacting the total quantity of quinoa harvested in a year is captured in Table 2.1.

Table 2.1: Number of Yearly Frost Days and Associated Historical Probability during the Quinoa Planting Season (September - May).

Number of frost days	Historical probability
0	0.2778
1	0.0556
2	0.1667
3	0.1667
4	0.0556
5	0.0556
6	0.0556
7	0.1111
> 7	0.0556

Source: Own illustration based on data from SENAMHI (2017)

Let us define $W_t \in [0; 30]$ as the number of days events randomly taking place during the planting season.[10] Table 2.1 captures the observed historical probability of the number of frost days. Assuming an unchanged distribution over time, these probabilities will be used in our model to form expectations about the number of frost days to be expected during the planting season each year.

Estimating the impact of frost on the harvest of quinoa

Quinoa production is sensitive to negative temperatures. Analyzing historical data, we observe a negative correlation (-0.14) between the number of days with frost during the planting season and quinoa production.[11]

To find out the relation between the number of yearly frost days and quinoa production, we run the following univariate regression:

$$q_t = \alpha + \beta W_t + \epsilon \tag{2.5}$$

Fitting Eq. 2.5 on historical data proved to be a very challenging task due to very poor data quality available for the region of interest. Faced with this uncertainty, we chose to run the model for a set of benchmark assumptions and then lead a sensitivity analysis around these values. We set α equal to the average annual quinoa production per hectare (expressed in kilograms per hectare) and $\beta = -2$ for the business-as-usual scenario.

Equation 2.5 captures how the quantity of quinoa harvested in year t is affected by frost. The computed expression is used to complete the definition of yearly profits in Eq. 2.1.

2.6 Results and Sensitivity Analysis

This section presents the results for the optimal times to invest in the long-term adaptation options that are expected to increase the total revenue of quinoa small farmers.

All models have been calibrated for the Arapa region in Puno. The analysis also focuses on the way the results change when varying important model parameters, in

[10]The historical data available for Arapa includes only one registered event that had more than 7 days of frost during the quinoa planting season in the period 1996 - 2014. Namely, in the quinoa season 2000 - 2001, 26 days of frost have been registered.

[11]The coefficients have been calibrated for Arapa in the Peruvian Altiplano over the period 1996 - 2012, based on yearly observations.

particular governmental subsidies for implementation, sensitivity of quinoa production to frost, and movements in quinoa prices. The decision horizon of the quinoa farmer is assumed to spread over 20 years. Therefore, whenever the model shows that the optimal switching time is 20, it should be interpreted that the option to invest is not actually optimal for the entire decision horizon of the farmer. Whenever the expected optimal stopping time is 1, it should be interpreted that the farmer is expected to invest in the following year, as implementation is assumed to require some time.

2.6.1 First option: Crop Management

In this section we present the results regarding the optimal time to switch from a business-as-usual quinoa variety to a different one. Quinoa varieties have different characteristics, in particular in terms of production yield (kilograms per hectare) and crop resistance to frost. Depending on the underlying characteristics, it might be beneficial for the farmer to abandon the quinoa variety he is usually planting in favor of a different one. The real option approach allows us to assess not only whether such a switch would make economic sense, but also to determine the optimal time to do so.

We focus our analysis on three quinoa varieties typical for the altiplano in the Puno region. The three varieties are Illpa, Salcedo, and Kancolla, and they have been identified as the most prevalent in the region by the quinoa farmers in the survey led by Senahmi and MeteoSwiss in December 2016 and also by their commercial relevance as described in the Catalogue of Commercial Varieties of Quinoa in Peru (FAO, 2015).

Table 2.2 captures the production characteristics of the three quinoa varieties considered, as well as the source where the information was gathered from. In the benchmark scenario, we assume that the sensitivity to frost is the same for all quinoa varieties, and we relax this assumption in the sensitivity analysis later on. As well, under the standard set of assumptions, the model fixes the cost of switching from one quinoa variety to another at 10% of the quinoa revenue in the year the switch takes place. This assumption is relaxed later on.

Table 2.2: Production Characteristics of Three Quinoa Varieties Typical for Altiplano.

Variety	Yield (kg/ha, Alpha in Eq. 2.5)	Time to physiological maturity (days)	Production cost (USD/kg)	Sensitivity to frost (Beta in Eq. 2.5)
Illpa	1,672	130.3	0.1038	-2
Salcedo	1,906	129.5	0.1038	-2
Kancolla	1,929	133.6	0.1038	-2
Source:	Bertero et al. (2004)	Bertero et al. (2004)	Mujica Barreda (1997)	Own

Table 2.3 captures the main results when the option to switch from the business-as-usual quinoa variety to a different one is considered. As each of the three quinoa varieties represents the status quo for some of the representative farmers in the Puno region, we run the analysis for all combinations of varieties. The purpose is to comprehensively assess the benefits of transiting from each quinoa variety to each alternative variety. The model reveals that, under the benchmark assumptions, the Kancolla variety dominates the Illpa and Salcedo varieties. Otherwise stated, farmers who currenty plant either Illpa or Salcedo quinoa varieties would benefit from switching right away to the Kancolla one, as this would increase their total revenues. The result is reflective of the fact that Kancolla has a higher yield per hectare than the other two varieties considered, while the other characteristics are held constant.

Table 2.3: Expected Optimal Time to Switch Quinoa Varieties under Benchmark Assumptions.

	Switch to		
Switch from	**Illpa**	**Salcedo**	**Kancolla**
Illpa	-	1	1
Salcedo	20	-	1
Kancolla	20	20	-

Sensitivity to the cost of switching quinoa varieties

Under the benchmark case, we showed that the Kancolla variety is the most profitable one and, consequently, farmers should consider adopting it as soon as possible. However, this result holds as long as switching costs do not surpass the benefits of the change. The cost of switching from one quinoa variety to another was assumed to amount to 10% of the total revenue in the year the switch takes place. In this section, we relax this assumption and check whether and when it is optimal to switch to Kancolla, given a large range of switching costs.

Figure 2.5 illustrates the results for the optimal switching time from the Salcedo to the Kancolla quinoa varieties at different levels of the switching cost. The results capture a very high sensitivity of the decision to switch to the level of cost. Incurring a cost of 16% of the year's revenues delays the decision to switch by fifteen years; a further percentage increase in cost renders the option to switch worthless. This high sensitivity to the switch cost is reflective of the fact that switching quinoa varieties from Salcedo to Kancolla results in only modest increases in total revenues that can be easily swiped away when the change is costly.

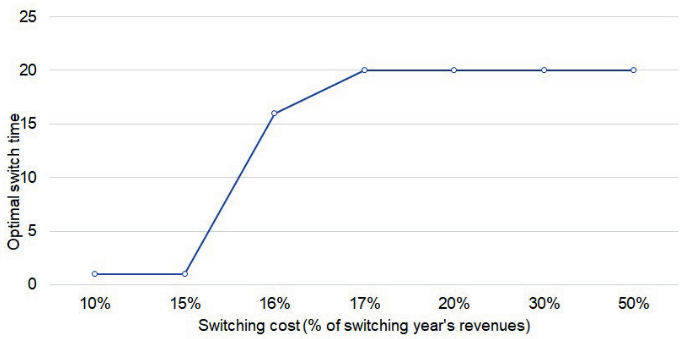

Figure 2.5: Expected optimal switching time from the Salcedo quinoa variety to the Kancolla one at different levels of switching cost.

Sensitivity to frost resistance

Our results so far have revealed that the Illpa variety is the least profitable one and the farmers who currently cultivate it would be better of by adopting either the Salcedo or Kancolla varieties as soon as possible. This result is based on the lower yield per hectare attained by Illpa compared to the other two, all other conditions equal. However, there is high uncertainty regarding the ability of the different quinoa varieties to resist to frost. In this section, we explore whether a higher frost resistance of

Illpa compared to the other two quinoa varieties would render it more profitable in the aggregate and, therefore, a good option to switch to.[12]

Figure 2.6 shows the optimal time to switch from Illpa to either Salcedo or Kancolla varieties, when the resistance of Illpa is held at the benchmark level (beta = -2) and the resistance to frost of the other two varieties is allowed to take values between -2 and -10. It is striking that under the considered scenarios, it is never optimal to postpone the decision to switch from Illpa to the other two varieties, no matter the level of resistance to frost. This result is important in that it highlights the reduced role that the resistance to frost has in comparison to the long-term trend in quinoa yield.

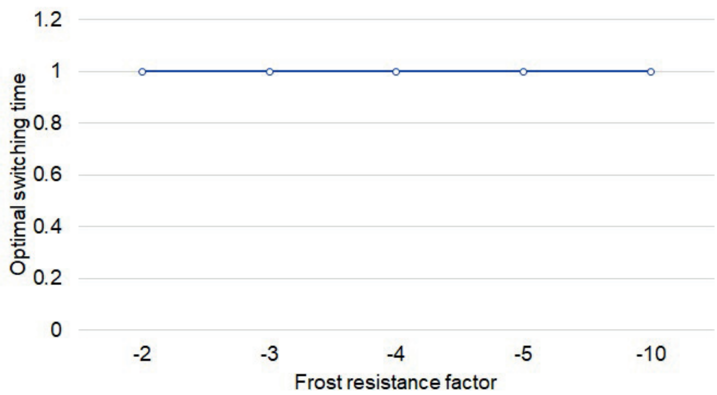

Figure 2.6: Expected optimal switching time from the Illpa quinoa variety to the Salcedo one at different levels of sensitivity to frost of Salcedo.

For completeness, we also run the model for the situation in which the sensitivity to frost of Salcedo and Kancolla is kept at the benchmark level (beta = -2), while that of Illpa is assumed to be very low (beta = -1). Table 2.4 confirms that even under this scenario, the farmer is better off switching to the Salcedo or Kancolla varieties, as this would increase the farmer's total profits.

[12]For the purpose of this study, the estimated optimal investment decision is based on maximizing total expected profits and does not include the personal preferences or traditional values of the farmer. In reality, the choice of quinoa variety can be influenced also by the farmers' past experience, choices of the peers, and even NGOs or local governments.

Table 2.4: Expected Optimal Time to Change Quinoa Varieties when the Resistance to Frost of the Illpa variety is -1 and for Salcedo and Kancolla is -2.

	Switch to		
Switch from	**Illpa**	**Salcedo**	**Kancolla**
Illpa	-	1	1
Salcedo	20	-	1
Kancolla	20	20	-

2.6.2 Second option: Waru Waru

In this section, the analysis is focused on the farmer's option to invest in the implementation and maintenance of the Waru Waru farming technique. Although fairly expensive, this long-term investment decision is expected to bring important benefits in terms of increase in quinoa yield and reduction in the crop's sensitivity to frost. However, the research on the exact magnitude of these benefits remains scarce, leaving a high uncertainty regarding the parameters the yield (alpha) and frost sensitivity (beta) parameters. Our review of the existing literature leads us to the decision to consider a benchmark case where the sensitivity of quinoa to frost under a Waru Waru regime is kept at the same level as under the business-as-usual, while the increase in quinoa yield per hectare is 20% higher under Waru Waru than under business-as-usual. These assumptions are relaxed further on.

Our model finds that, under the benchmark assumptions, the implementation and maintenance costs needed to ensure a good functioning of the Waru Waru system are prohibitively high and it is never optimal for the farmer to invest in this option. The following sections illustrate how this result changes when we vary the assumptions regarding the key parameters.

Quinoa price and sensitivity to frost

We first analyze the scenario in which the market for quinoa becomes stronger over time and this increase in market maturity is reflected in prices that tend to increase on average over time, and experience only limited down movements. The idea behind this analysis is to be able to pinpoint whether better quinoa prices would overcome the high implementation costs and render Waru Waru a viable option.

Fig. 2.7 below illustrates the optimal time the farmer is expected to invest in the Waru Waru option when the magnitude in the down movement in prices is allowed to vary, all other conditions constant. We find that, under all considered scenarios, the Waru Waru option remains infeasible, as even always increasing quinoa prices (magnitude of down movement = 0) are not sufficient to justify the high Waru Waru investment cost.

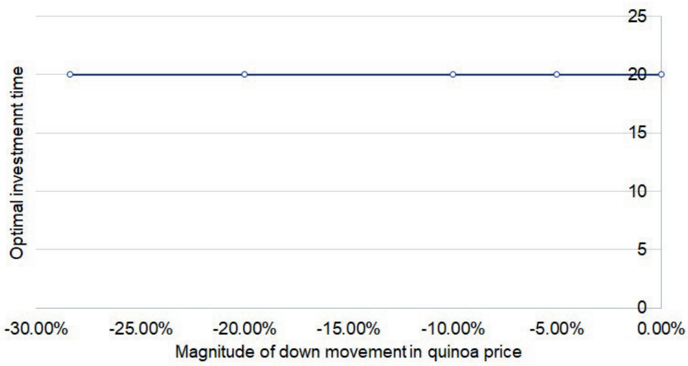

Figure 2.7: Expected optimal investment times in Waru Waru at different quinoa price changes.

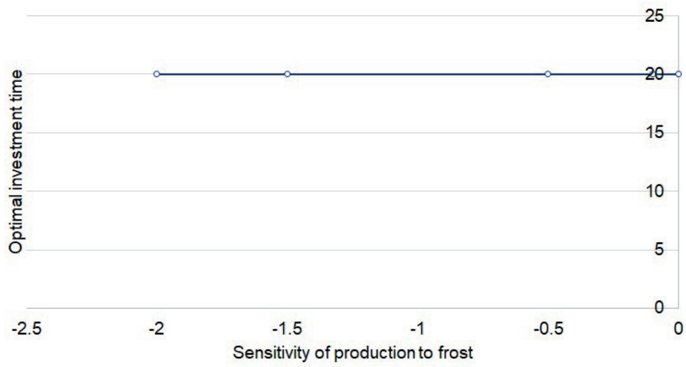

Figure 2.8: Expected optimal investment times in Waru Waru at different sensitivity levels to frost.

As mentioned above, one of the advantages of the Waru Waru technique is that it decreases the sensitivity of quinoa to frost events and, thus, guarantees better yields in years with many or severe frost events. Fig. 2.8 captures the results for the optimal decision to invest in Waru Waru when the sensitivity of production to frost under Waru Waru is allowed to be lower than under the business-as-usual. We find that, despite helping achieve a much lower sensitivity to frost, the implementation cost of Waru Waru is still too high compared to the potentially increased revenues. Even when the sensitivity to frost under Waru Waru is completely wiped out (beta = 0), the farmer would be better off under the business-as-usual. As in the case of the first option, i.e. switching the quinoa variety, the role played by the resistance to frost parameter seems limited.

Governmental subsidies and increases in productivity

The previous section has shown that the current estimates regarding the implementation and maintenance costs of the Waru Waru technique are too high for the quinoa farmer and it appears optimal for him to remain under the business-as-usual scenario. In this section we test the robustness of this result by further relaxing the assumptions related to some key model parameters.

First, we are interested in understanding whether some governmental support, in the form of subsidies for Waru Waru implementation, would increase the value of the Waru Waru option and by how much. Fig. 2.9 illustrates the sensitivity of the optimal investment time in Waru Waru at different levels of governmental support. We find that only an almost full (above 80%) subsidy of the implementation cost would render the Waru Waru option interesting for the farmer. The results seem to be highly sensitive to the level of subsidy in this high range, where increasing the subsidy from 90% to 100% would lead the farmer to optimally expedite the investment decision from year 18 to the present year.

Although high governmental subsidies could become feasible in a world where Peru aims to establish itself as a world leader in quinoa production, it remains unlikely that subsidy levels took such high values to render the investment in Waru Waru optimal right away.

Next, we analyze the attractiveness of the Waru Waru option for different levels of increases in productivity compared to the business as usual. The uncertainty for the effect of Waru Waru on quinoa productivity is high and we, thus, consider a broad array of values. As a brief comparison, it has been estimated that the increase of patato production under Waru Waru is 40% higher than under the business-as-usual (Mujica Barreda, 1997). We find that, indeed, the impact of the Waru Waru technique on quinoa productivity plays a major role in the decision to adopt quinoa; see Fig. 2.10. At an increase in the productivity of quinoa of 40% under Waru Waru, the option to invest in this technique is optimal in year 12 of the investment horizon. The results are highly sensitive to increases in productivity above the 40% level, such that at 60% an imminent investment in Waru Waru would be optimal.[13]

[13]The values considered by our study for the increase in productivity due to Waru Waru are only

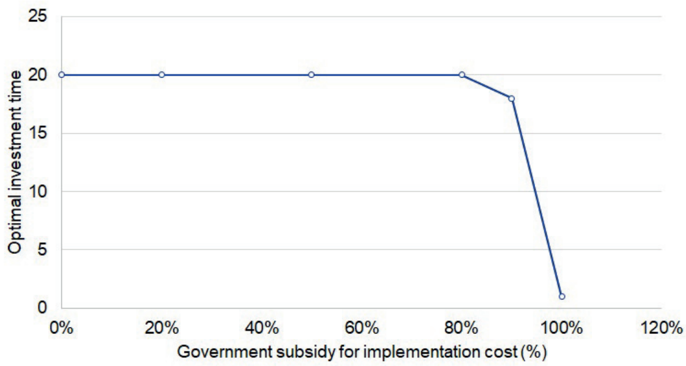

Figure 2.9: Expected optimal investment times in Waru Waru at different levels of governmental subsidies for investment costs.

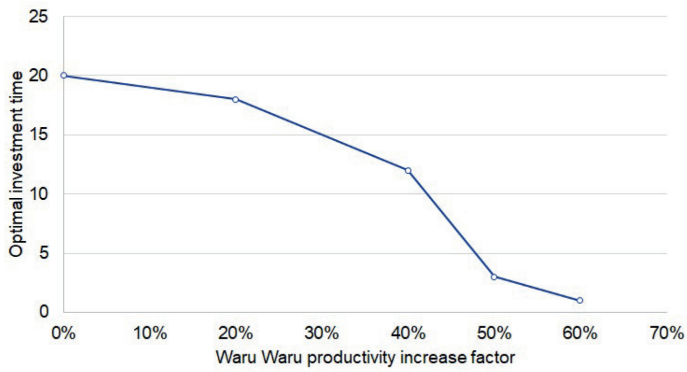

Figure 2.10: Expected optimal investment times in Waru Waru at different levels of productivity increases.

Having discovered the paramount role that the increase in productivity under Waru Waru plays for the feasibility of this investment option, we revisit the role of governmental subsidies. Fig. 2.11 captures the results for the optimal investment times when both the increase in productivity under Waru Waru and the level of government subsidies are allowed to vary. We find that even a modest support from the government (subsidy of 10%) would trigger a fast investment in Waru Waru at increases in productivity above 30%. The results are even more striking for higher subsidies.

Our results signal the importance of leading further investigations regarding the capacity of Waru Waru to increase quinoa yield. Once the uncertainty regarding this parameter is lowered, clear recommendations could be formulated regarding the optimal timing for the farmers to adopt this option. The potential role of the govern-

illustrative; further research could bring evidence for or against some particular values.

ment in supporting regional development appears to depend on this key parameter as well.

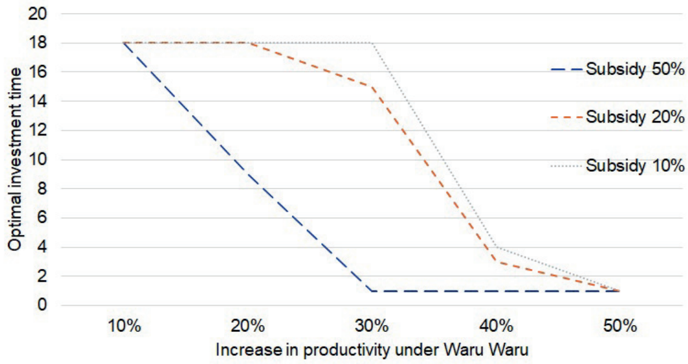

Figure 2.11: Expected optimal investment times in Waru Waru at different levels of governmental subsidies for investment costs and of productivity increases.

2.7 Conclusion

This article focuses on the decisions a smallholder quinoa farmer in the Peruvian altiplano faces in order to increase his profits. We rely on a Real Options approach that accounts for uncertainty in future quinoa prices and weather events that impact the yearly quinoa yield. The Real Options approach is a technique that, similar to NPV, assists a rational decision-maker in evaluating an investment decision. However, contrary to the NPV approach, Real Options allow for more flexibility in the decision-making process and account for the possibility to postpone an irreversible decision until more information is gathered regarding the stochastic variables.

In this article, we have evaluated two long-term investment options, namely (i) quinoa variety management and (ii) the Waru Waru farming technique. Regarding the first option, our results show that, depending on the current quinoa variety, switching to a different one might be optimal immediately, as better varieties exist that are suitable for the Altiplano and provide higher yields and consequently larger profits. In particular, the Kancolla variety has the highest yield and should be considered right away by quinoa farmers that are currently relying on the Illpa or Salcedo varieties. However, we also show that the decision to adopt new quinoa varieties is highly sensitive to the cost incurred when the switch is made, be it the cost of new seeds or of learning how to handle this new variety. Our results also show that the sensitivity to frost of the different quinoa varieties remains a factor with low power to influence the investment decision. Investment decision is based only in the results of the assessmnet and does not include any personal preference or traditional values of the farmer.

Regarding the second option, we find that investing in Waru Waru is prohibitively expensive for the quinoa farmer, under benchmark assumptions. However, a few factors seem to play a crucial role in the optimality of the investment decision. Importantly, it has been estimated that the Waru Waru technique increases the yearly quinoa yield, by so much as 40% for potatoes. The estimates for the impact of Waru Waru on quinoa production lack scientific evidence, leaving room for high uncertainty around this key feature. Our study further puts emphasis on the importance of solving this uncertainty, as our results show that for productivity increases above 20% the quinoa farmer is expected invest in the Waru Waru option in the medium-term future, and at increases above 50% the investment should be immediate. One needs to be cautious when interpreting these results, as high uncertainty remains regarding the actual productivity increase due to Waru Waru. We also analyze the role that governmental support could play for the development of the quinoa market through incentives at the smallholder level. We find that governmental subsidies for the implementation of Waru Waru could play a significant role in bringing the optimal investment time closer to the present, especially at increases in productivity above 20% compared to the business-as-usual.

Our study made best attempts to lead an accurate analysis and formulate clearcut results that could be relevant for practitioners, policymakers, NGOs, and other stakeholders. However, we also tried to emphasize throughout our report the high uncertainty surrounding many of the key parameters of the analysis. Our results should therefore be interpreted with great care and adapted to the specificities of the context of interest. It is also important to acknowledge that, although the results are sensitive to assumptions, the methodological approach embraced in this study is robust and can be applied to a variety of contexts. Further investment options and different geographic regions could easily be accommodated in a future study.

Acknowledgments

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Chapter 3

What are you waiting to invest in grid-connected residential solar energy in California? A real options analysis.

with Prof. Dr. Marc Chesney, University of Zurich

A version of this paper has been submitted to Renewable and Sustainable Energy Reviews.

Abstract

The goal of this paper is to assess the optimal choice of a household in California, United States, in terms of their decision if and when to undertake a certain investment in a residential scale, grid-connected, solar photo voltaic system, in order to obtain savings in their monthly expenditures in electricity. This irreversible option is then defined, mainly, by the initial cost of the solar PV system. For this purpose, Real Options Analysis is deployed to assess this investment opportunity for the household. This approach allows determining not only whether the investments should be undertaken or not, but also the optimal timing to do so. Results show it is optimal for a Californian household to invest in a photo voltaic system, however some delay might be advised depending on the energy production factor of specific areas, and the expected useful life of the equipment. Furthermore, government intervention influencing subsidies and energy prices has a major effect in the length of such delays.

3.1 Introduction

In 2016, the state of California[1] accounted for one-tenth of the population of the United States and steered an economy of over $2.3 Trillion U.S. Dollars. Statistically, adoption of solar photo-voltaic (PV) energy was still scarce in the rest of the country at that time, but not in California (Barbose et al., 2017). With over 6.18 million kW[2] of PV installed, the state alone accounted for 47.9% all solar power of the United States in 2016. Roughly 50% of all PV projects reported in the U.S. are claimed to be residential, close to 60.6% of all PV projects in California (over 3.74 million kW of the installed PV in the state) are residential. How can the boom of residential solar PV projects in California be explained? Is it worth investing in residential solar PV projects in this state? And if so, is it still optimal to invest there in view of market price dynamics of electricity, investment cost and expected technological advancements in the foreseeable future?[3]

Real option assessment (ROA) models are dynamic and allow to identify optimal investment time and level. In terms of investments, the usual decision making tool used is time value of money, and particularly, Net Present Value (NPV). According to this methodology, an investment should be triggered if and only if its value, i.e. the difference between its expected discounted payoffs and costs is positive. The NPV criteria is static to the extent to which the implicit choice is between realizing the investment at the date when it is calculated, or never. This is a significant drawback of this criterion.

In general, the household has the right, and not the obligation, to make an investment during a given period of time for up to 20 years in this case. The life-cycle of the given project presented in this setting also accounts for up to 30 years, given the existing solar PV technology. When identifying the optimal investment date, the possibility of postponing it is also taken into account. An option also includes the economics of irreplaceable assets and stress that performing an irreversible action at one point in time involves the cost of renouncing the flexibility to wait; if this cost is correctly taken into account in a cost-benefit analysis, in order for the action to be economically justified, the benefits from the decision must be higher than in a traditional cost-benefit analysis.

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[1] 39 million inhabitants.

[2] Kilowatts.

[3] According to a CNBC in 2018 ”California remains the undisputed leader when it comes to solar power in the U.S., with almost 23 GW of installed solar.”

Price of the PV panels in California

In terms of the investment decision assessed in this paper, the main component of cost is determined by the initial investment on a residential scale, grid connected, solar photo-voltaic system[4] in order to obtain savings in their monthly expenditures in electricity. It is common belief that the cost of solar panels has been reducing for the last decade, and also that technology has improved to a current point of efficiency that has reduced the unitary investment cost in solar panels. Which is in fact true. However, for the scope of this study we center in the total amount of the initial investment of PV project, rather than only including the cost of the panels. This investment amount is based on real data reported on PV projects installed in the state over the last decade, which have also declined as it will be explained below. Overall investment cost reductions, in any case, have also triggered debate on the convenience to give continuity to the incentives for solar investment available in the state for many years. This work addresses both of those components in our estimates.

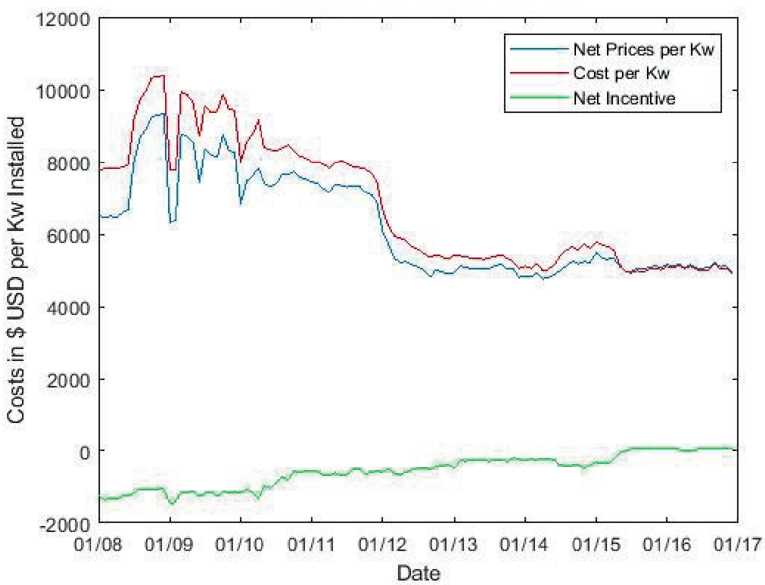

Figure 3.1: Historical cost of PV Panel Systems by kW in California, own illustration. (Barbose et al., 2017)

As we can observe Figure 3.1, for costs in USD per kW installed, historical data shows very interesting trends on the cost of investments in PV between 2008 and

[4]For further reference, see Figure 3.3 in the Appendix.

2016. In this figure we can observe three distinct lines, the red line portraying the cost of PV systems as reported by the installer and excluding any incentives or subsidies. The blue line shows the same investment cost including the effect of incentives or subsidies, in case they were obtained and so is described as the Net Price per kW of the system. Lastly, the green line shows the amount of any reported incentive or subsidy.

Here we can observe two important trends. First, investment cost of PV systems are, in fact, declining over time, while the use of incentives or subsidies has also reduced. Since incentives or subsidies reduce the investment amount of households investing in solar PV systems, and it is always optimal to use as much of incentives as possible, then it can then be inferred that this reduction is likely motivated by the availability of such incentives or subsidies. However, the reduction of net investment cost in PV systems seemed very pronounced between 2010 and 2012, it becomes is quite flat after 2015. And finally, we can also notice that the net effect of incentives and subsidies is very close to zero after mid 2015.

Historically prices of PV panels in California are presented from self reported projects by their developers and/or investors. For the purpose of this study, only 122,859 of those records resulted relevant. Criteria for relevance including filtering only projects reported as Residential, that were appraised by third parties, had a range of cost between \$10 and \$1,000,000 USD, and an installed capacity ranging between 1 and 30 kW, in order to reduce noise. PV costs were retrieved from the OpenPV Database, that offers 1,020,672 records of solar installs in the United States. The OpenPV database offers the cleaner dataset "Tracking the Sun 10" (Barbose et al., 2017) that is published annually and provided more relevant observations. As self-described by the National Renewable Energy Laboratory, "The Open PV Project is a collaborative effort between government, industry, and the public" and was a very complete source of historical data. This dataset is voluntarily contributed from a variety of sources, and while information available can be extensive it was not always relevant.

Electricity residential rates dynamics in California

Electricity rates[5] used for the calibration of this model include monthly average data between January 2001 and December 2017. For the dynamics of prices in California we can clearly identify three important trends described below. For the simulation

[5]Also known as electricity prices.

of electricity rates, we account for all three trends in order to obtain a more accurate result.

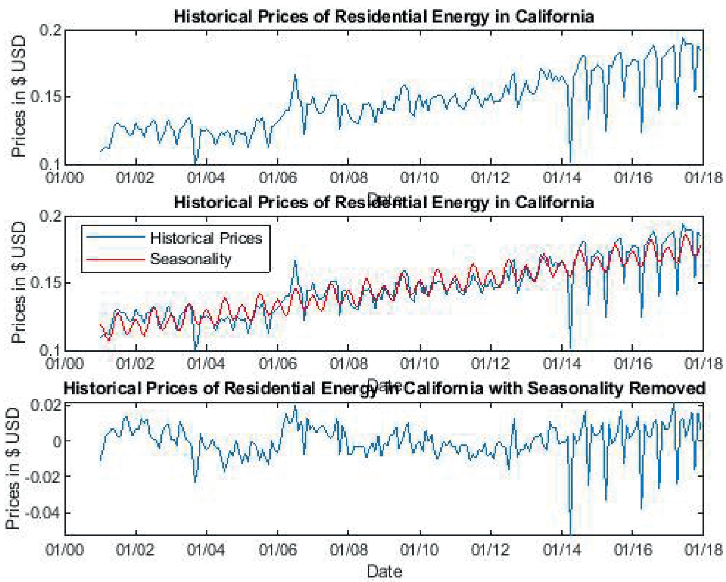

Figure 3.2: Historical electricity rates to residential customer in California. (U.S. Energy Information Administration, 2018)

Energy residential rates in the state of California show three very clear trends seasonality, increase overtime and identifiable recurrent negative jumps. Seasonality, as mentioned above, is addressed on this model by subtracting it before the calibration of the model and adding it back to be accurately reflected in the simulations. The increasing trend is easily replicated by the process chosen for the estimation. Lastly, the negative jumps are also adjusted every 6 months, in the months of April and October since 2014. In the detail in figure 3.2 we can notice how those negative jumps as base prices increase. No evidence was found on the motivation nor criteria used by the utility companies for determining this adjustment, and so an scenario without the effect of such adjustments or negative jumps is presented in section 3.5.3 below.

Historical electricity rates were retrieved from the U.S. Energy Information Administration, Form EIA-861M (formerly EIA-826), Monthly Electric Power Industry Report. U.S. Energy Information Administration (2018). Ultimately all data analyzed in this paper was obtained from public databases of the U.S. Department of Energy, which resulted to be extremely relevant for the analysis presented in this paper.

This paper includes an analysis on PV project data, residential energy prices and subsidies for PV energy at State level for California, but it could easily be scaled for data for other states in the country[6]. This paper can also be a baseline for new developments in the PV market, not only for residential solar energy but also for non-residential and utility-scale projects. For the purpose of these study, 10,000 Monte Carlo simulations were produced.

This paper is organized as follows: Section 3.1 gives an overview of the state of research in ROA, particularly for solar PV energy in California and the United States, including the current development of this technology, and also provides a general framework on historical prices of residential electricity, which are both relevant for our model. Section 3.2 gives an overview of the literature on research in ROA and in particular for the energy industry. Section 3.3 outlines the model and the numerical method used in our model and the choice of parameters. Section 3.4 introduces the case study of California and the variables used for the setting defined and our model assumptions. Section 3.5 gives the main results and the key findings in the sensitivity analyses of our results. Section 3.6 concludes.

3.2 Literature Review

A number of studies in the Economic literature have addressed solar PV project investments. It has been in fact a recurring topic in academic journals over the last two decades and has covered different geographies, perhaps showing more regularity for the United States and western Europe. One early example can be found with Wiser (1997) that explores different ownership and financial structures for the investment on renewable energy (RE). Wiser mostly centers on utility scale wind energy projects, but even if his scope falls a bit outside of the scope of this paper, his conclusion clearly touches a sensitive assumption of this model, by affirming that costs can vary highly, up to 40% in his case, by the simple effect of changes in financing structure and ownership. Faiers and Neame (2006) present an interesting survey that shows among other things, that "The success of the UK policy to reduce carbon emissions is partly dependent on the ability to persuade householders to become more energy efficient" and by such affirmation establishes a clear relevance of solar energy in that country.

Later Fouquet and Johansson (2008) introduce the two main forms of incentive

[6]Not all states report enough projects to the OpenPV project database in order to allow for a fair assessment.

systems to promote RE in the European Union (Feed-in-Tariffs and Tradable Green Certificates) by establishing that "a target for RE penetration is set by public authorities seeking to minimize cost for achieving this target." That in a way is still relevant today since RE projects pose the interesting potential for savings and reduced environmental impacts but still have a significant up-front cost. The authors of that article also highlight the preference of users to up to incentives as Feed-in-Tariffs (FiT) provided theirs in countries like Denmark, Germany, and Spain. Frondel et al. (2010) on the other hand, contradict the supposed success of the Feed-in-Tariff system implemented in Germany.

Dusonchet and Telaretti (2010) go a little bit further and assesses the economic potential of PV projects in different western European Union countries, and obtains interesting results in a comparison that shows some limitations of different incentive schemes implemented at national level. Results of the comparison presented are very complete, however the methodology for this paper bases the analysis on Time Value of Money that is a static valuation methodology. Klein and Deissenroth (2017) indicate that "Stepwise changes in the remuneration design can therefore induce non-linear and non-intended investment behavior" however the novel part of their analysis focusing on prospect theory, they apply their model to an NPV methodology. As mentioned by the authors "The value function of prospect theory. The disutility of losses is comparatively larger than the utility of gains of the same absolute size. The shape of the value function can be measured experimentally." Escribano et al. (2011) works with the "evolution of electricity prices in deregulated markets" and unveils interesting elements on how to deal with seasonality and mean reverting processes in energy. Bull et al. (2011) start to introduce the U.S. into the scope by analyzing the implementation of Feed-in-Tariff systems in California and New York. The authors also include analysis in the Reverse Action Mechanisms also implemented in California as a form of incentive, and stress the importance of such incentives to continue to promote the development of distributed RE at an adequate pace. Martin and Rice (2018) further go into the complexity of designing and implementing "a fair and reasonable retail FiT policy". They also evaluate the convenience on the level of government regulation on that matter and further discover that stakeholders perceptions on this matter end up being shaped geographically.

Drury et al. (2012) at once enter the southern Californias residential PV market by exploring its evolution through third-party ownership, and it continues to be a key component of such investments, however third party ownership can be perceived as a proxy for positive economic returns, since on rational investors would be involved in such a scheme. The authors suggest two very interesting finding, the former that third-party owned residential PV systems are rapidly growing when regulation allows for them, and the latter that at the time of that study, evidence suggests that reducing price barriers from $6 to $4 USD/Watt (after incentives in both cases), was not sufficient to attract new investments in PV systems. Something very interesting, considering the current situation of the market in California, as it is further described in this paper. Schelly (2014) reviews the phenomenon of early adopters of residential solar PV projects. This study suggests three main points: "(1) environmental values alone are not enough and are not always necessary, to motivate adoption; (2) rational economic calculation in the narrow sense of calculated return on investment or payback period is less important than the particular timing of economic events within a household; and (3) perceiving oneself as an early adopter is only important for some, while communication through social networks occurs in the context of communities of information." In a way, Schelly's findings reinforce the importance of assessing uncertainty as a key component in the decision. A potential benefit then has to be perceived, but it in essence has to be, both, as certain and positive as possible. Wolske et al. (2017) find that although households in the United States perceive solar PV in a positive way: "as an environmental benefit, a consumer good, and an innovative technology" when promoting such investments to households, marketing efforts have to emphasize more on "non-environmental benefit" even for environmental concerned individuals. It still seems to be a hard sell.

Some authors even engage to compare PV project markets in Europe and the U.S., as Seel et al. (2014) provide evidence showing that in 2012 "Residential photovoltaic (PV) systems were twice as expensive in the United States as in Germany (median of $5.29/W vs. $2.59/W)" which is quite a reveling finding. Further update on this trend would be useful, however, these findings do not contradict the clear reduction in price of the PV systems observed, but rather indicate that soft costs piling up into the total investment value of a system are key factors to consider. Wüstenhagen and Menichetti (2012) summarize strategic choices for RE investments. In particular one important aspect touching solar PV projects in recent years is the dramatic reduction on the cost of the systems, Candelise et al. (2013); Bazilian et al. (2013) present some work on different forecasting methods for PV system pricing. Pillai (2015) suggests that "the upstream industries that supply the solar panel industry with raw materials and capital equipment have been important contributors to the reduction in the production cost of solar panels" which can in a way contradict the popular believe that solar panel cost has reduced mainly on technological advancement and efficiency, but also allows to more conservative estimates for further assumptions on price reductions.

The general setting of this paper is based on the work of Bauner and Crago (2015); Chesney et al. (2017a) and establishes the benchmark of a typical household with an investment irreversible option to install a solar PV system. Although Bauner and Crago (2015) present an application only for the state of Massachusetts, their model of adoption of residential solar power under uncertainty is quite relevant to the scope of this work. These authors center their work on the implications of their finding over incentives. They "determine optimal adoption times, critical values of discounted benefits, and adoption rates over time for solar PV investments", which is in line with the objective of this paper. Their results reach that "policies that reduce the uncertainty in returns from solar PV investments would be most effective at incentivizing adoption." Their analysis is deep, and the methodology implemented by this authors is dynamic, allowing to better assess uncertainty in potential savings, which is quite novel, but their assessment of data for Massachusetts allowing them to state that "despite generous financial incentives the adoption rate is low." is not necessarily the case in California, which allows for further exploration in the most relevant solar PV market in the United States. Kim et al. (2017) also propose a ROA model to assess RE investment decisions in developing countries. They offer an application of ROA in developing countries which is quite novel, however, their analysis includes a binomial lattice for calculating compounded of options that, although dynamic, is rather simplified. Matisoff and Johnson (2017) explain that "Results suggest that approximately 67% of state and utility incentives, up to $1.9 billion over 11 years, were likely spent on incentives that did not increase residential solar PV installations". Yet again it is clear that incentives are decreasing, but also that they are not implemented in the most efficient way.

Some studies like Luthander et al. (2015) explore the impact of self-consumption in several countries in a world of decreasing subsidies. They even go a step further and analyze the so called demand side management (i.e. energy storage and load management). Other studies like Kastner and Stern (2015) go even further and review 26 empirical studies on the decision-making processes behind household energy investments. Among their findings, perhaps the most relevant is their affirmation on the progress of behavioral research on this field. "About half the empirical studies we considered were completed during the past five years.” Showing that this is still quite a novel field of research, but one obtaining major relevance at an increasing rate. Salm et al. (2016) explore the relation of risk-return preferences towards RE projects for retail investors in Germany. Among the findings of this study we can observe that opossed to professional investors, retail investors “use simple decision rules such as calculating payback time or relying on their gut feeling when making investment”. Castellanos et al. (2017) explore the potential of Rooftop solar PV in cities. Vaishnav et al. (2017) explore the dramatic fall in subsidies in the United States in 2014, which is clearly consistent with our analysis. Krupa and Harvey (2017) goes into analyzing RE finance in the United States and determines the effect of subsidies which actually result in net financing rates that fall below the assumptions of this study. Mazzucato and Semieniuk (2018) probe financing renewable energy: Who is financing what and why it matters “Financial actors vary considerably in the composition of their investment portfolio, creating directions towards particular technologies. Public financial actors invest in portfolios with higher risk technologies, also creating a direction; they also increased their share in total investment dramatically over time.”

On looking for further possibilities to enrich the scope of this we work, it can be mentioned that some work has been done on Real Option Analysis regarding climate change that could also be extrapolated to energy modeling. Chesney et al. (2017a) elaborate on more on this are by introducing risk aversion in Real Options while assessing the optimal choices of a forest owner given his option to enter an irreversible scheme that provides uncertain cash flows under different risk aversion scenarios. Chesney et al. (2017b) present in a dynamic setting a model for mitigation of global warming. This is in a way the same situation in which this paper is written, provided that households are also faced with the irreversible option to enter an investment with uncertain cash flows and perhaps within different risk aversion scenarios. For this paper the risk aversion of the investor is not relevant to their rational decision to invest or not in solar panels to obtain potential savings, but risk aversion could be nevertheless a great element to further explore within this setting in future work. Even more, considerations of game theory and competition could also be included to asses competition in such a dynamic market as California; Botteron et al. (2003) propose a model that could also be adapted to that purpose. Finally another important aspect to consider when talking about solar PV energy is storage. Besides the entry barriers already highlighted, production intermittency is the other key challenge to solve. Hoppmann et al. (2014) discuss this through a simulation, which could also be included in a further extension of this research. Futhermore, Rai and Robinson (2015) incorporate the integration of social, behavioral, economic, and environmental factors in a model of energy technology adoption. This could also be a nice to have in further work. Ng and Tao (2016) present different schemes to promote renewable energy financing in Asia though bonds. This aiming to the financing gap for renewable energy. Lam and Law (2016) go beyond to establish green financing schemes for renewable and sustainable energy projects through Crowd-funding. Potential financing alternatives seem to be attractive also to assess on further work.

Our model examines the current dynamic of residential grid connected PV systems in California from the perspective of the household. We assume that the decision maker knows investment amount but has uncertainty about potential savings in order to make an optimal decision, in terms of investment timing.

3.3 Model and Numerical Methods

The present study describes some basic properties of the ROA aiming to increase and apply the methodology to assess savings for a typical household[7], while taking advantage and deciding the optimal investment time. This is done specifically for the case of a typical house in California. The general setting of this paper is based on the work of Bauner and Crago (2015); Chesney et al. (2017a) and establishes the benchmark of a typical household with an investment irreversible real option to install a solar PV system. The household is assumed to minimize their sum of expected expenditure in electricity k_t, and faces a trade-off between expected savings and the initial investment, given that the invested amount I_t is known, while the energy price is uncertain. The household decision-maker is assumed to be rational. The investment decision can be triggered any time t.

The household then has a benchmark opportunity (Business as usual or BaU) to obtain their full electricity supply from the grid, or alternatively, the option A to invest in solar PV system, that would allow them to obtain potential savings in the long run of between 20 and 30 years, n, provided that the household implements the stated irreversible option A. In both cases, P_t is the electrical rate per kWh in USD, and Q is the amount of energy to be consumed in kWh. Grid interconnections also allow to efficient disposition of the totality of the energy produced, meaning that the

[7]Representative Agent Model.

amount of electricity to be produced and consumed can be considered to be equal. The BaU scenario is defined by:

$$k_t^{BaU} = P_t Q \tag{3.1}$$

Under option A, if P_t increase, the potential savings are high, and vice-versa. Since we focus on potential reduction in expenditures, after undertaking the investment option, the household expenditures on electricity are offset by the savings resulting from self production. Then, only the marginal cost of the energy not produced by the investment which theoretically would be seamless, assuming the household is self-sufficient to supply their energy with the installed PV system. In equation 3.2, k_t^A now represents the amount of potential savings, rather than the cost of energy for the household, once the option is implemented. The potential amount of electricity to be produced by the named solar project is defined by ϕ, the Energy Production Factor or EPF, of the corresponding location of the household, that can adjust for the uncertainty of real electric production of the PV system[8]. ϕ is the amount of energy that can be produced in a year according the installed capacity of a PV system in kWh/kW-year. Equation 3.2 also identifies the possibility of some operational or financial cost over time C_t, i.e. in case the project obtains third-party financing, requires additional variable cost, or duties for residential energy production were introduced the future.

$$k_t^A = \phi P_t Q - C_t \tag{3.2}$$

Equation 3.3 includes the net amount of the initial investment I_t in equation, where $I_t > 0$. This amount adds the installation cost N_t, a potential subsidy or rebate S to be received by the project, but also, any potential reduction of the initial capital disbursement in case of third-party financing is obtained for the project that could also be included potentialy.

$$I_t = N_t - S \tag{3.3}$$

The difference between the energy costs of the two scenarios, with and without solar PV energy production can then be defined by Ω in equation 3.4. The first right-hand side term is the total cost of energy over n years $[20; 30]$ without solar, and the second term is the net cost of energy with the solar PV system (including the invest-

[8]See note in Figure 3.4 in the Appendix.

ment). For the household, if $\Omega \geq 0$, total energy cost is lower with the installation of solar panels. If the investment is started at time t, we have:

$$\Omega_t = \mathbb{E}\left[\sum_{u=t}^{t+n} k_u^A e^{-r(u-t)} - k_u^{BaU} e^{-r(u-t)} - I_t e^{-rt}\right] \tag{3.4}$$

The household will decide when to invest in the option, aiming to minimize their total expected future expenditure in electricity discounted over time:

$$\min_{\tau_A \in T} \Omega_{\tau_A} \tag{3.5}$$

Where T is a set of stopping times, and represents the time at which the household decides to invest in the project[9]. Now, the household has the option to delay the investment. Under this setting, the traditional NPV criteria would no longer hold for the household, and even if potential savings exist at a certain point, given that delays cannot be captured by NPV. And so the household could choose to defer the investment, even infinitely. Both P and N are stochastic and follow Geometric Brownian Motion as defined below:

$$\frac{dP_t}{P_t} = \alpha_1 dt + \sigma_1 dB_t \tag{3.6}$$

$$\frac{dN_t}{N_t} = \alpha_2 dt + \sigma_2 dW_t \tag{3.7}$$

Where both B and W are Wiener processes normally distributed with zero mean and variance. The drift and the volatility are denoted by α_ν and σ_ν respectively ($\nu = 1, 2$). We also assume zero correlation exists B and W since the underlying of both processes are independent, one relying on electricity rates and the other on the dynamics of pricing of project investments.

3.3.1 Assumptions regarding the model variables

There are some major Assumptions regarding the model variables. On one hand, the price of residential electricity is one important variable for our model, especially when observing its evolution over time. To model the price dynamics, we rely on

[9]Let $(\Omega, F, \{F_t\}_{t\in I}, \mathbb{P})$ be a filtered probability space, i.e. a probability space equipped with a filtration of σ-algebras. Then the random variable τ_A is a stopping time if $\{\omega \in \Omega : \tau(\omega) \leq t\} \in F_t$, i.e. the decision to stop waiting and to invest is only based on historical data.

the historical distribution of residential electricity as provided by the U.S. Energy Information Administration (EIA). Prices denote important seasonality and volatility that had to be modeled accordingly. On the other hand, cost of investment in solar PV technology has observed a very particular trend of unprecedented reduction, in parallel of technology advancement on energy production. In other words, solar PV technology has become and is expected to increasingly be cheaper and more efficient than it historically was.

In addition of that, starting in April 2014, we can observe significant discrepancies in the evolution of electricity rates for the months of April and October respectively. In such months, a corresponding reduction of γ_1 and γ_2, of approximately 70.4% and 79.68% are observed, in comparison to the expected value of such months under other circumstances. Such price cuts are adapted to the model by including the following indicator function for ${P_t}'$, see equation 3.8. Results of this adjustment can be observed in table 3.4 presented in Section 3.5 of this work.

$$\begin{aligned} P_t' = & P_t[(1+\gamma_1)\cdot \mathbb{1}_{t\in[4+j\cdot 12;4.99+j\cdot 12]}] + \\ & P_t[(1+\gamma_2)\cdot \mathbb{1}_{t\in[10+j\cdot 12;10.99+j\cdot 12]}], where\ j \in \{\ 0,...,20\ \} \end{aligned} \tag{3.8}$$

Finally, an important goal of the paper is to demonstrate the usefulness of real option models in Photovoltaic investments, while assessing the benefit of revenue increase for households which has in the past been limited to stressing the advantages of the technique rather than reflecting on specific applicability of the methodology. It is innovative to apply this methodology for this particular setting and region. In fact, although solar PV projects have been a recurring topic in the assessment of different Economic Studies, Real Options Analysis has been applied mainly to other fields and it has been much limited to a handful of studies published several years ago, which means that these studies do not include current price conditions specifically for California.

3.4 Case Study and Altenative Option

The case study considered in this case is the one of a typical household in California. Based on the chosen parameters, the households' optimal decision shows savings that solely come from the installment of the PV system. The detail on the parameters used for the model calibration can be found in Table 3.1 below.

As mentioned above, the household has two alternatives: Business as usual, the

Table 3.1: Model calibration parameters.

Parameter	Explanation	Value	Sensitivity Analysis	Sources
I_t	Initial investment cost	$5,055 USD/kWh	see Figure 3.1	(Barbose et al., 2017)
$P_t(0)$	Residential energy rate	$0.1848 USD	see Figure 3.2	(U.S. Energy Information Administration, 2018)
Q	Installed PV capacity	5.5519 kW	-	(Barbose et al., 2017; U.S. Department of Energy, 2016)
ϕ	Efficiency Production Factor, also EPF	1	[0.9; 1.1]	(U.S. Department of Energy, 2016)
C_t	Variable cost	0	-	-
τ_A	Starting point of the investment	-	[0;20]	-
α_1	Drift of electricity rates	1.50E-17	-	-
σ_1	Volatility of electricity rates	0.009773012	-	-
α_2	Drift of PV costs	-0.002580	-	-
σ_2	Volatility of PV costs	0.064289	-	-
i	Discount rate	0.004808		HELOC Interest Rate
dt	Time steps	1/360	-	-
n	Useful life of the Panels	20	30	-

benchmark case, i.e. "do nothing," or to invest in a PV System. The former offers no perceived benefit on savings from the perspective of the household since they are assumed to consume a given amount of energy for the time considered in the present study. The latter, however, allows the household to obtain certain savings provided that they invested in a PV system that satisfies their consumption. All energy produced and consumed by the household is assumed to be equal, assuming net metering in a grid connected system[10], meaning that they either consume as much energy as they produce or they save it by supplying any excess of production to the grid to consume it in the future. The household is also assumed to either consume the energy produced (and any energy saved on the grid) during the length of the scope of this analysis in order to perceive such benefits.

3.5 Results

3.5.1 Main option: Invest in a PV System

In the presence of boundaries limiting their maximum possible saving, the household faces an important irreversible decision: to invest in a solar PV system or not. For an expected ϕ[11] = 1,900 we can see how this decision should be to invest now, in the best case, wait to invest for up to 5.3 years in the benchmark case, or to wait almost 12.5 years in the worst case. This describes how uncertain the decision scenarios for the household are. The choice of scenarios in this case is resulting from the

[10]For further reference see figure 3.3 Appendix.

[11]Energy Production Factor, also EPF represents the amount of energy to be produced by each kW of PV installed capacity, this amount is determined on average by geographic location and determined in kWh/year. Further detail on different geographic areas of the U.S. is provided in the appendix, see 3.4

expected performance of PV projects according to their potential ϕ. Most projects, according to their location would tend to perform within a range of +/- 10% of their expected ϕ according to U.S. Department of Energy (2016).

3.5.2 Sensitivity Analysis

As we can observe in table 3.2, different energy production factors along the state of California result in different expected delays for the investment. Areas with the highest ϕ clearly seem to suggest more immediate investment, while areas with the lowest ϕ even suggest delaying the investment[12].

Table 3.2: Expected Optimal Time to invest in PV system with an estimated useful life of 20 years (in years).

EPF Scenarios	**1,500**	**1,600**	**1,700**	**1,800**	**1,900**	**2,000**	**2,100**
Best Case (+10%)	14.75	10.33	6.25	2.75	0	0	0
Benchmark	>20	17.08	12.58	8.75	5.33	2.08	0
Worst Case (-10%)	>20	>20	>20	16.08	12.42	8.75	5.75

Source: Own illustration

3.5.3 Other options

In order to observe the sensitivity of the optimal investment time we also assumed two additional independent alternatives to run the scenarios, as we can observe on the following tables. Either to extend the expected useful life of the projects to 30 years (see table 3.3), or to eliminate the negative jumps in energy rates (see table 3.4):

[12]For this setting, >20.00 suggests that the evaluation did not find an optimal stopping time within 20 years.

Table 3.3: Expected Optimal Time to invest in PV system with an estimated useful life of 30 years (in years).

EPF Scenarios	**1,500**	**1,600**	**1,700**	**1,800**	**1,900**	**2,000**	**2,100**
Best Case (+10%)	0	0	0	0	0	0	0
Benchmark	6.00	1.75	0	0	0	0	0
Worst Case (-10%)	13.25	8.67	4.58	1.00	0	0	0

Source: Own illustration

In Table 3.3, it can be observed that in the best case scenario of a project with an estimated useful life of 30 years, which is in fact achievable under current state of technology, we encounter significant improvements in the reduction of the investment delay, which immediate in several scenarios, but does not exceed 6 years in the benchmark case of any of the geographies nor 13.25 years in the the worst case scenario for the geographic area with the least energy production potential.

Table 3.4: Expected Optimal Time to invest in PV system (in years) without the effect of negative jumps.

EPF Scenarios	**1,500**	**1,600**	**1,700**	**1,800**	**1,900**	**2,000**	**2,100**
Best Case (+10%)	11.92	7.58	3.67	0.33	0	0	0
Benchmark	18.75	14.17	10.00	6.00	2.58	0	0
Worst Case (-10%)	>20	>20	17.42	13.17	9.50	6.00	3.08

Source: Own illustration

Based on table 3.4, it can be determined that compared to the results shown in table 3.2 the effect of these negative jumps can result in delays on the investment of between 2.5 to 3 years in most cases. This is an important impact, and it could indicate that areas with highest ϕ could be optimal for more immediate investments, although they seem to be negatively affected by the artificial control of residential energy rates in the months of April and October.

3.6 Conclusion

For this ROA setting, we have been able to determine a Californian households optimal decision time when choosing to invest in a residential solar PV System to obtain potential savings in their electricity expenditures. The choice has strong implications for the household. Entering this scheme is an irreversible decision that provides the household with uncertain savings, and implies an important and certain up-front investment. In order to be as realistic as possible, our model considers different scenarios for pricing that are believed to be conservative. From the household's perspective, reasoning is merely profit maximization, between the increasing prices of energy, given the discount rate and a technically immediate big investment required to trigger uncertain benefits. The household does not have an incentive to undertake the investment unless potential savings are high enough, as also explained by Schelly (2014) and Salm et al. (2016). For those households, the sooner they undertake it, the sooner they will start to save money but are in no rush. And in the best case, those savings are not clear enough that they would rush into their decision. The initial investment is always certain, and the outcome, is not.

Results of this study show that even though the potential of savings is clear, it might be optimal to wait somewhere in between 5.5 and 12 years in some cases, which is clearly a drawback. Apparently resulting from the expected variability of energy production of the projects, but also from incorrectly assessing the useful life of the project or provided some manipulation in the energy rates, as explained in section 3.5. Important potential savings can be observed as long as the initial investment is not too high. And it is precisely that initial investment in many cases what makes the delay in the investment to be so reasonable. As mentioned by Seel et al. (2014) projects can be twice as expensive in the United Estates than in Germany, and soft-costs are an important part of it. In reality subsidies and other incentives do not seem to be any longer a relevant component of the investment decision of Californian households, but they could be tuned to other relevant purposes, i.e. energy storage and panel recycling that could become the next big problem to solve in the realm of solar PV energy.

Regulators have an important part in order to promote more efficient markets for PV solar systems that are ultimately less costly to the Californian household. However, their efforts seems to potentially go, both, in favor and against of more residential PV investments in the state. In recent times, contrasting regulation reforms have been discussed in California. Two of which are worth highlighting. On one hand to implement minimum tariffs on solar energy production, and in the other, to establish a minimum requirement of solar production for new construction of building of over three stories high[13]. The former would represent additional cost on top of the new tariffs already imposed by the Federal government of the United States on the import of PV systems and components, along with estate level regulation regarding fixed monthly charges[14] for residential electricity. A decision in this direction could alter the evolution of PV system prices and electricity rates. Furthermore the artificial pricing of electricity rates, i.e. significant reductions every six months, have a deep impact on the optimal time of the investment decision according to the findings of this work. In contrast, new building rules approved by the California Energy Commission in may 2018 seem to favor a more optimistic situation for residential PV energy in the state.

Finally, even-though the scope of this study centers on the perspective of an individual investor, the household in California, the macro effects of the finding of this study are relevant for the United Stated and not only to the state of California. In 2016, the total of the installed residential PV capacity has surpassed 6.49 and 3.74 million kW respectively. This in a way also results in important policy implications, provided the supply of solar energy in the state can also influence the overall electricity rate levels market dynamic at national level. As mentioned above, California can opt into different policy strategic directions, but it seems like the state will continue to allow and in a way promote the development of residential solar energy, which would be consistent with the finding of this study. In a way, it could also set the bar for other states and even countries to follow.

[13]At the time that this article was written, only the latter had passed.

[14]If implemented, this charges could set a floor price for energy limiting the potential of savings described in this work. No fixed monthly charges are expected to be introduced before 2020.

Appendix

Grid connected PV system

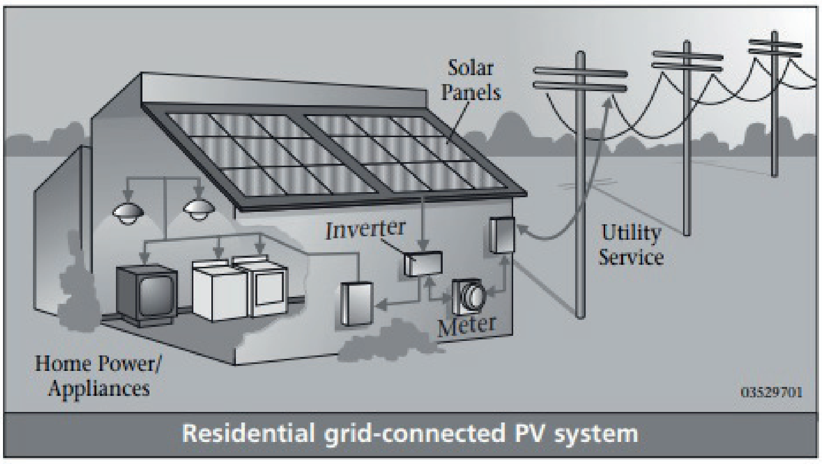

Figure 3.3: Diagram of a typical grid connected PV system.
(U.S. Department of Energy, 2016)

Energy production factor (EPF) in the United States

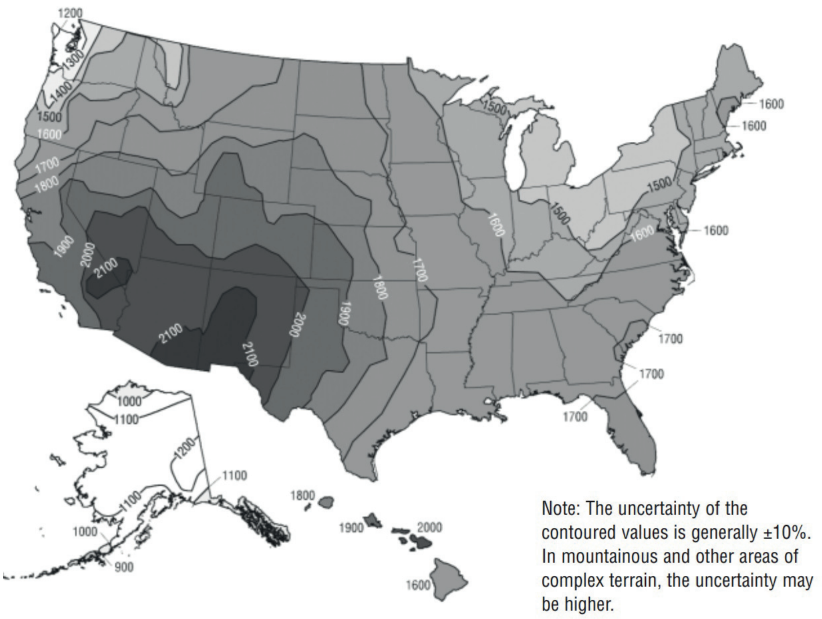

Figure 3.4: Energy production factor (EPF) by geography in kWh/kW-year.
(U.S. Department of Energy, 2016)

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Chapter 4

End of Life decommissioning and recycling of Solar Panels in the United States. A real options analysis.

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Abstract

It is estimated that hundreds of thousands of tons of solar panel waste are going to be produced yearly just in the United States from the year 2035 on, most of which could be recycled. This paper estimates the amount of scrap material to be produced from solar photovoltaic panels decommissioning and determines the optimal date and location to establish centralized or regional recycling centers to better deal with this issue on its early stages, between the years 2024 and 2042. Solar panel recycling could become a multi-billion USD industry over that time, however the main challenge today is to keep its overall costs down while allowing for the mayority of panels to be recycled. Real Options Analysis is deployed to assess the optimal solution to face this challenge. This approach allows determining the optimal time and location to invest in recycling centers and the best strategy to undertake among different alternatives. The goal of this paper is to set a cornerstone for dealing with solar panel decommissioning and recycling at the end of their useful life in the United States, and we also determine a model that accounts for optimal location of the recycling facilities, which is a novel approach. This paper also offers a new application of the ROA modeling for estimating the optimal investment date for solar panel recycling plants from the investor perspective of the U.S. government in Washington D.C. Further applications of the model proposed in this work could allow for a similar analysis at an international level.

4.1 Introduction

Solar energy is one of the most common forms of renewable energy, and it is typically classified as green energy. Economic and environmental benefits resulting from the production of energy from photovoltaic (PV) panels or modules are widely studied and its convenience is hard to question. This affirmation regards only the operation of panels but sets aside the rest of their life-cycle. Solar photovoltaic energy, like any other energy production form, has its downsides, and it can yield a significant amount of waste. In particular, solar energy offers important environmental advantages while producing energy, but triggers salient impacts resulting from the production and transportation of the PV panels, and at the end of life (EoL)[1] of those same panels. All this tenders important opportunities for reuse and recycling of materials that significantly improve the life-cycle performance of the panels environmentally and financially. This work explores alternatives regarding the best disposal management of the panels and explores whether or not it poses a noteworthy investment opportunity.

Recycling PV panels is necessary for environmental and financial reasons. Crystalline Silicon Panels are the most common PV panels installed to date. According to experts, they represent 85 to 90% of the market[2]. They are mostly manufactured with aluminum, glass, silicon, copper, and plastics (DAdamo et al., 2017), which can be recovered at very high rates, and in most cases convey significant economic value. The recycling process for PV panels includes chemical and physical treatment approaches, which have been successfully implemented by other industries, i.e. consumer electronics recycling. We believe that the technical part of the process has been well determined and studied by experts in the field, and we center our approach to determining the financial viability of these processes. PV panels also contain other hazardous components, i.e. heavy metals and other toxic elements, that require special treatment and are typically encapsulated inside plastic elements in the panels. Processing those plastics results in an additional cost to the overall process and deteriorates the quality of plastics to be recovered from the panels, which is recognized financially in our approach.

Solar panels also tend to be big and heavy, and so they frequently exceed the allowance for conventional waste management centers in different locations. In addition to that, Crystalline Silicon Panels do not typically pose interesting profits to

[1] End of life is a term used to describe that the useful life of a product has been exhausted.

[2] Our numbers show an even higher proportion, as it can be seen in section 4.1.1 of this work.

recyclers as they do not contain significant precious or scarce metals, however, the equipment to produce 1 MW of energy with this technology can weight around 75 tons on average (DAdamo et al., 2017). In many cases, recycling the panels can be very efficient, and reach between 78% to almost 100% efficiency of recovering for some components (DAdamo et al., 2017). After the panels are processed, glass, silicon, plastics, and copper recovered can be used to manufacture new panels. Solar PV panels have a useful life that can range from 25 to 30 years in most cases. The question here is what should happen to the panels after their operational life has been exhausted. There certainly could be a problem to handle the equipment is treated like trash, as they would annually represent more than: "3 million tons [of waste] in 2035 to 9.5 million tons in 2050" (Bakhiyi et al., 2014), but also for the hazardous components present in the panels, that cannot be dumped to the landfill.

Recycling the panels could result in an interesting financial opportunity. In a 2016 report by IRENA[3] (Weckend et al., 2016) it was detailed that recovered materials from the panels alone could be worth $450 million USD by 2030 and exceed $15 billion USD by 2050. We know with relative good certainty where a lot of those panels are located within the U.S. We cannot know, however, the exact time of deployment, provided different investors may have specific capital requirements for their projects, and we can expect some exogenous events to occur,[4] affecting the expected useful life of the panels, but we can estimate the time of deployment stochastically, as described in Section 4.3, provided that data regarding their installation and useful life is readily available and some of such events can be estimated.

4.1.1 Solar energy in the United States

In the United States, PV panels started to ground in the 1970s but did not become a hot topic until the 2000s. It was only until two decades ago that renewable energy was targeted to reduce emissions and to diminish our reliance on fossil fuels. Between 1999 and 2017, 26.6 thousand Megawatts of PV were installed in the U.S., 69.8% alone over the period of 2013 to 2017, and 11.4% of which corresponds to the year 2017. Solar panel installations between the years 1999 and 2017 have grown by 184.4% on average for that period (Barbose et al., 2017).

Installed solar PV capacity in the United States represents an estimated 2 million tons of solar panel scrap to be produced between 2024 and 2042, under general as-

[3] International Renewable Energy Agency.
[4] Examples of such events are described in subsection 4.1.3.

sumptions, further detail can be observed in table 4.1. Actually, the factors explained in section 4.1.3 below, could result in accelerated decommissioning of the panels and higher estimates. With these numbers, the United States could be the second market by potential solar PV waste production, behind China and ahead of Germany and India.

Table 4.1: Installed Solar PV Capacity in the United States.

Year Installed	Installed Capacity (in kW)	Estimated Scrap (in tons)
1999	953.21	71.49
2000	696.32	52.22
2001	4,666.67	349.97
2002	22,633.93	1,697.41
2003	24,294.76	1,821.96
2004	37,078.48	2,780.66
2005	42,943.72	3,220.52
2006	65,715.64	4,928.28
2007	116,387.72	8,728.38
2008	204,232.00	15,316.17
2009	929,568.88	69,712.09
2010	3,003,921.70	225,276.17
2011	2,223,006.21	166,712.13
2012	1,362,354.12	102,168.39
2013	5,721,665.06	429,090.55
2014	1,821,191.13	136,578.41
2015	2,252,238.89	168,904.40
2016	5,767,794.60	432,549.99
2017	3,033,668.86	227,506.96
Total	26,635,011.89	1,997,466.09

Source: Based on data from Barbose et al. (2017)

Of the total installed PV panels in the U.S. between 1999 and 2017, only 6 states concentrated 94.81% of that capacity. Arizona and California were the states with most PV panels in kW, respectively with 52.20% and 25.77%. Meanwhile, Massachusetts, Utah, New York, and Colorado accounted for an aggregated 16.85%. Finally, other 19 states[5] aggregated together with the remaining 5.19% of the national total. The rest of the states did not report installed capacity to this dataset. Further

[5]Arkansas, Connecticut, Delaware, Florida, Illinois, Kansas, Maine, Maryland, Minnesota, Missouri, New Hampshire, New Mexico, Ohio, Oregon, Pennsylvania, Texas, Vermont, Washington D.C., and Wisconsin.

detail on installed PV capacity by the state can be found in table 4.2. The six states with the most panels are located all over the United States geography. While California is localized in the west very close to Arizona, New York, and Massachusetts are in the east. Colorado and Utah can be found in the center part of the country.

Table 4.2: Installed Solar PV Capacity by the state in the U.S.

State	Percentage of total installed panels
Arizona	52.20%
California	25.77%
Massachusetts	7.87%
Utah	4.03%
New York	3.65%
Colorado	1.30%
Other 19 states[5]	5.19%

Source: Based on data from Barbose et al. (2017)

4.1.2 Solar panel recycling

Solar PV recycling seems to be a relatively unexplored field internationally. Some areas such as the European Union have specific directives regarding it, such as Waste Electrical and Electronic Equipment Directive (also known as WEEE Directive) which was originally established to deal with general electronic recycling, but also includes provisions for solar panels. By the time this paper was written, the United States had not passed significant regulation regarding this issue, except for California that attempted to establish rules to manage solar panel waste, i.e. ”Proposed Standards for the Management of Hazardous Waste Solar Modules” in 2010. Although that piece of legislation was limited and did not seem to cover implementation thoroughly, also was not in effect at the time that this article was written. Other pieces of regulation, i.e. the ”Universal Waste Management Regulations” have been recently passed by the state regarding this topic, and are yet to be implemented, but the scope of these regulations to solve this issue is not completely clear at this point in time.

Perhaps the best approach could come directly from the industry, i.e. First Solar, the biggest American solar panel supplier, and organizations such as PV Cycle[6], that specializes in PV recycling, as they self describe ”waste management and legal

[6]See: www.pvcycle.org

compliance services for companies and waste holders around the world." They offer recycling services throughout a decentralized network of collection points in certain geographies aiming to breach the gap between end-consumers of the panels and the recycling process. According to Reuters[7], a joint effort between Veolia and PV Cycle France resulted in the first European solar panel recycling plant in France just in 2018. The facility was set to recycle 1,300 tons of solar panels in 2018 is expected to be able to reach 4,000 tons by 2022.

4.1.3 Factors affecting the useful life of the panels

As above mentioned, the useful life of the panels is typically 25 years but can reach 30 years in some extraordinary cases. The estimated useful life includes an expected decay of the equipment by regular use. As mentioned above, sometimes panels can exceed that expectation, but in some cases, they are also deployed early for different reasons, i.e. due to some of the following factors:

Accelerated degradation and defects

Regardless of their expected useful life, solar panels sometimes incur in early failures. Warranties in most cases cover defects, however, it is difficult to ship back the defective panels to the producer, and while the equipment gets replaced, the responsibility of disposal of the defective equipment remains with the end-consumer. Also during their lifetime, PV panels can develop defects and experience performance degradation due to local stresses. The defect type and rate of degradation depend on several factors, i.e. cell technology, manufacturing quality control, installer workmanship, and the installed environment, etc. Defects can be diverse, from purely cosmetic, to sometimes causing safety risks (Jordan and Kurtz, 2011).

Also, according to Jordan and Kurtz (2011) "for monocrystalline silicon, the most commonly used panel for commercial and residential PV, the degradation rate is less than 0.5% for panels made before 2000 and less than 0.4% for panels made after 2000." This is just the normal degradation of the panels and does not account for increase degradation resulting from the above-mentioned factors. It is typical to consider a 20% decline on the production capacity of the panels to be considered failure, but it does not seem to be clear a consensus on it.

[7]See: https://www.reuters.com/article/us-solar-recycling/europes-first-solar-panel-recycling-plant-opens-in-france-idUSKBN1JL28Z

Natural phenomena

Some panels get damaged for weather events or other eventualities. But where are those panels going now? According to experts, to the landfill, since "there is no dedicated national program or requirement to safely dispose of the panels, and some, unfortunately, find their way into the landfill" Pickerel (2018). The question then is, who should be responsible for the disposal of those panels in the U.S.? We have on one side the producer that is sometimes regarded liable for what they offer to the market in some geographies, i.e. in Europe with the WEEE Directive, or on the other side, the end consumer who is acquiring the equipment and this case should assure that it gets properly disposed of. Perhaps, we could also appoint waste managers and ultimately local, state and federal governments responsible to deal with health and safety of civil society. Some liberals may even argue that the market itself should be allowed to self regulate into dealing with the issue. The truth of the matter is that there is no answer yet, at least not in the United States. This, in fact, goes against the promise of solar energy to be clean an renewable source of energy. Pickerel (2018) also presents a comprehensive report on claims for solar PV panels in North America. According to it, weather-related events were the most common reason for claims, approximately 49.8% followed by fire with 36.1% and electrical breakdown with 9%. Other causes roughly reach 5% of the claims and include mechanical breakdown, lightning, and theft. And it seems that provided increased weather-related events and wildfires in the United States, an increase in claims can be expected. According to Kelly Pickerel, innovation could be an alternative to make more resistant panels, but still, the challenge results from already existent panels.

Investor preference

In addition to the typical external scenarios of deployment, we can also observe, that in some cases, older projects were installed in the best locations. This motivated by the added effort needed to achieve profitability at the state of technology when that happened originally. Those locations also resulted interesting for renewed investment today and can be incorporated in a further application of the present work, provided the current state and a projected state of technology. Innovations tend to pose opportunities are a great set point for real options. As it is well known, innovation is not a recent phenomenon. Modern industries deal with innovation on a regular basis, and while innovation usually implies a certain investment that can eventually be recovered or not, it does promise potential benefits. In such case, it is just a rational expected response from investors to opt to refurbish or completely rebuild their solar capacity as new technologies reach a certain level of improvement, to take advantage of the best locations, as it would be more profitable in the long run. In our setting, this would accelerate the expected end of life of the panels. Other factors affecting the expected life-cycle of the panels exist, and could be analyzed, although not enough documentation can be found at the time, and therefore further research is needed.

4.1.4 Real Options

Real option assessment (ROA) models are a great fit to identify optimal stopping problems, such as the problem stated in this paper where we try to anticipate the optimal investment date for a recycling facility. These models are used in order to check whether investment decisions should be taken and when is the optimal time to do so. Besides these models, the standard tool used in this setting before was time value of money, and particularly, Net Present Value (NPV). This methodology, an investment should be triggered if and only if its NPV, i.e. the difference between its expected discounted payoffs and costs is positive.

The criteria for NPV is then static to the extent to which the choice is between realizing the investment at the date when the NPV is calculated, or never. This is a significant drawback of the NPV criterion. NPV also assumes that cash flows and cost are known, in other words, as long as there is certainty in the amount and frequency of the cashflows an estimation can be made in NPV. In the case that cashflows are uncertain, ROA is found to be a more useful tool to value investments. ROA is also useful to assess value when an investment can be delayed.

4.1.5 Sections

This paper is organized as follows: Section 4.1 gives an overview of the current status of end of life management of solar PV panels installed in the United States and describes the problem that we address in our research. Section 4.2 gives an overview of the existing literature regarding this issue and also describes some of the previous efforts to apply ROA in particular for electronics decommissioning, end of life management and recycling. Section 4.3 outlines the model and the numerical methods used to solve it and the choice of parameters deployed. Section 4.4 introduces the case of the United States and the variables used for the setting defined and our model assumptions. Section 4.5 gives the main results and the key findings in the sensitivity analyses of our results. Section 4.6 concludes.

4.2 Literature Review

Renewable energy is a frequent topic to academic work, and so it is to the field of Real Options Analysis. As it would be expected most exertion regarding renewable energy can be found regarding investment, financing, feed-in-tariff schemes, but recycling and end-of-life assessment of solar PV panels is a relatively new topic. Our article contributes to the literature by developing a dynamic real options model that allows determining the optimal time to invest in the best strategy to undertake among distinct possible alternatives.

Seminal work on End-of-life management and recycling of PV panels started with Fthenakis (2000). In this work, the author highlights the environmental advantages of PV technology and presents a feasibility study for recycling thin-film solar cells and manufacturing waste, based on the current collection and recycling infrastructure, but also based on current and emerging technologies. Cucchiella et al. (2015) present a traditional Net Present Value financial analysis on End-of-Life of used photovoltaic panels, and they state that the scientific literature presents divergent technological solutions, and highlight the environmental benefits resulting from the PV panels recycling, but conclude that the economic arguments are more fragmented.

Technical aspects of PV recycling can be found in the work of Doi et al. (2001), Klugmann-Radziemska et al. (2010), and Berger et al. (2010). Klugmann-Radziemska and Ostrowski (2010) conclude that the disposal of PV systems will become a problem in view of the continually increasing production of PV panels. These can be recycled for about the same cost as their disposal. Fernández et al. (2011) even go further to present a study on the recycling of crystalline solar cells inside cement matrices. Rocchetti and Beolchini (2015) study how to manage valuable materials inside the panels through different recycling alternatives. Tao and Yu (2015) review the feasibility of recycling pathways and technologies of solar photovoltaic panels from three different pathways.

Latunussa et al. (2016) perform a Life Cycle Assessment (LCA) of an innovative recycling process for crystalline silicon photovoltaic panels. It is worth mentioning that LCA is also a favored methodology for assessing end of life management of solar panels provided the characteristic of this methodology to assess different impacts at the product level. Further reviews on innovative recycling methods for PV panels can also be found in the work of Shin et al. (2017) and Choi and Fthenakis (2010), that present the status of photovoltaic recycling planning and discuss a mathematical model of the economic feasibility and the environmental viability of several PV recycling infrastructure scenarios in Germany in 2010. An important paper that contributed significantly to the parameters used in this work was written by DAdamo et al. (2017), who describe in much detail the outcomes of the recycling of Si PV panels. The work of DAdamo et al. (2017), however only sets to analyze the global situation of PV recycling in a general way and describes a simplified NPV approach with linear price estimations that is enriched with the model presented in our work.

Renewable energy policy evaluation using Real Options model for Taiwan and China can be found in studies by Lee and Shih (2010) and Chi et al. (2014). Chi et al. (2014) study E-waste collection channels and household recycling behaviors in a region of China. McDonald and Pearce (2010) explore the responsibility of the producer in recycling solar photovoltaic panels. They even present detail on the cost of landfill disposal of different types of solar panels. One of the most comprehensive and earlier studies on the scale of the problem regarding the end of life management of solar panels is presented by Weckend et al. (2016). In this study, the authors determine panel waste volumes to 2050. Xu et al. (2018) establish a quantitative basis to support the recycling of PV panels, and suggests future options policy determinations.

Other Real Options Analysis work can be found in the field of climate change that could also be extrapolated to energy modeling. Chesney et al. (2017a) elaborate on more on this by introducing risk aversion in Real Options while assessing the optimal choices of a forest owner given his option to enter an irreversible scheme that provides uncertain cash flows under different risk aversion scenarios. Considerations of game theory and competition could also be included to asses competition once the market matures, and new entrants start to interest in this market, and such situation could by captured by a model such as the one proposed by Botteron et al. (2003). Besides the entry barriers already highlighted, intermittent production is the other key challenge to solve. Also, the model proposed by Rai and Robinson (2015) incorporates the integration of social, behavioral, economic, and environmental factors in a model of energy technology adoption. This could also be good to include in further research.

The financing gap that could result from the imminent interest in solar PV recycling could also result in a financing gap, such as the one that currently exists in solar PV investments and energy storage. Further research would be needed in that regard. Finally, research comparing different solar PV markets, i.e. the United States and Europe is also common, for an example, we can see Seel et al. (2014). Further work on recycling could also be done not only including those two markets, and China, India and other global players as presented by different authors (Chi et al., 2014; Zhang et al., 2016b; Lee and Shih, 2010; Ding et al., 2016; Weckend et al., 2016).

Although wind and solar seem to be the most persistent cases to be found in academic literature regarding applications of Real Options for Renewable Energy, since the early 2000s, it is also possible to find further academic work studying the different aspects of other forms of renewable energy. Typical examples include tidal, hydro, alternative fuels (ethanol, biomass, biogas, etc.), and renewable energy in general. Even further work can be found regarding nonrenewable forms of energy, i.e. Nuclear. Provided the scope of this work, that literature was not included in this summation.[8] Our work contributes to the existing literature by presenting a model that estimates the viability of distinct potential solutions for the PV recycling problem in the United States, accounting the uncertain timing of the life-cycle of PV panels and provided multiple market factors. The value added of this paper is that it assesses the problem of PV recycling in the United States before it becomes a problematic situation resulting in hundreds of thousands of scrap to be improperly disposed of. This model also deals with real options regarding the optimal location which is a novel approach.

4.3 Model and Numerical Methods

The present study describes some basic properties of ROA aiming to determine an optimal allocation of resources and timing for an investment in one or two solar PV panel recycling plants. Provided that existing panels are located in different states, our model assumes a rational decision from the perspective of the U.S. federal government in Washington[9]. The general setting of this paper is based on the work of

[8] For further reference regarding research on Solar PV investments, please refer to Vargas and Chesney (2019), included as chapter 2 of this compendium.

[9] Regarding this assumption, the authors recognize that there could be practical and political implementation issues that arise, and we discuss them further in Section 4.6 below.

Chesney et al. (2017a,b); DAdamo et al. (2017); Vargas and Chesney (2019), but also establishes the benchmark of a ROA model that can describe the problem at hand. We also further detail the main assumptions regarding key model parameters and elucidate on their calibration.

4.3.1 Model Setup

For this work, we take the view of the U.S. Government in Washington that foresees a number of solutions to deal with hundreds of thousands of solar PV scrap from 2024. They understand that all solutions could become costly, but recognize that the inclusion of revenue making input into their solution, could potentially reduce their own expenditure and even become profitable. In our setting, there is a benchmark case, and four long-term decisions that they could evaluate:

(BM) To delay the investment in a recycling plant as long as possible, paying only for storage cost, and assuming the recycling of the panels would have to be done eventually.

(A) To install one recycling plant that deals with all national solar PV scrap.

(B) To install two regional facilities in order to distribute the recycling between them.

(C) To improve existing consumer electronics plants to deal with solar PV scrap, taking advantage of economies of scale.

(D) To send the panels to be recycled in Mexico in order to take advantage of reduced operational costs.

The above options are very different, but the evaluation of their viability demands for a relatively similar decision process. We assume that the U.S. Government is a rational decision maker who would aim to reduce the cost of recycling panels whenever possible. We also assume that in case that the recycling is not performed storage cost is incurred (also described further as the benchmark case), which would be a costly alternative. We assume that the investment horizon of the U.S. Government is $[0; T]$; in our numerical solution, we consider $T = 19$ years[10] and a discount rate of

[10]Data for installed PV panels in the U.S. deployed for this analysis covers the years 1999 to 2017.

3% as suggested by DAdamo et al. (2017) and other experts[11]. ω_t^{BM} is the yearly cost to the U.S. Government under the benchmark corresponds to:

$$\omega_t^{BM} = \kappa_t^{st}(Q_t) \tag{4.1}$$

Equation 4.1 describes the factors that influence the potential yearly cost to the U.S. Government, where $\kappa_t^{st}(\cdot)$ is the cost to store the scrap PV panels, we believe that given that storage is a simple operation it can be handled locally. Q_t is the amount of panels (in tons) available for recycling during the years 2024 to 2042, assuming that panels are typically disposed after 25 years of useful life, and our data provides detail on the panels installed between the years 1999 and 2017.

We assume that all panels would have to be recycled sooner or later, and non-recycled panels from previous years would be recycled as capacity allows. With that aim in mind, but also trying to reduce their expenditure in the dealing with this issue, the U.S. Government has a set of long-term investment options they could undertake. We have identified 4 distinct options that are described below:

4.3.2 Option A

The first option in our model, also $Option\ A$, is to establish a national recycling facility. This one facility would deal with the whole volume of scrap PV panels generated nationwide and their yearly cost ω_t^A could be described by:

$$\begin{aligned} \omega_t^A = \kappa_t^p(Q_t, A) + \kappa_t^m \gamma^{Pl}(Q_t, A) + \kappa_t^{tr}(Q_t, \Phi, A) \\ -P_t^{Al}\gamma^{Al}(Q_t, A) - P_t^{Cu}\gamma^{Cu}(Q_t, A) - P_t^{Gl}\gamma^{Gl}(Q_t, A) - P_t^{Si}\gamma^{Si}(Q_t, A) \end{aligned} \tag{4.2}$$

$\kappa_t^p(\cdot)$ is the cost function of the recycling that depends on the amount available and the adaptation options already implemented[12]. Since plastics cannot be recycled, the yield of plastics obtained γ^{Pl} is adjusted by the cost to deal with conferred materials $\kappa_t^m(\cdot)$ and its product is an added cost to the recycling process. Finally, $\kappa_t^{tr}(\cdot)$ is the cost of transportation of the panels from one state to another, and it is a function Q_t but also Φ the average travel distance in between states[13]. This function also allows us to determine the optimal location for the recycling plant. We make the

[11] See: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf
[12] $\kappa_t^p(\cdot)$ includes the collection and processing of the panels.
[13] Intrastate transportation is already accounted for in the overall of $\kappa_t^p(\cdot)$

general assumption that only interstate travel is to be accounted for, meaning that any transportation cost within the state's limits is assumed to be zero.

P_t^{Al} is the time t price of recovered aluminum, P_t^{Cu} is the time t price of recovered copper, P_t^{Gl} is the time t price of recovered glass and P_t^{Si} is the time t price of recovered silicon from the recycling process[14], γ^{Al}, γ^{Cu}, γ^{Gl}, and γ^{Si} are the yields in kg/ton of each corresponding material to be obtained per Ton of recycling scrap material. Each material recovered is a function of the amount of panels available for recycling or Q_t and the long-term adaptation $Option\ A$ that has been already implemented. The proceedings of these materials reduce the overall cost of operation. Copper and Aluminum are two of the main components to be recovered from Silicon based panels (Si Panels), their historical price performance can be seen in Appendix A. P^{Al} and P^{Cu} are assumed to be stochastic and follow a Geometric Brownian Motion as defined below:

$$\frac{dP_t^{Al}}{P_t^{Al}} = \alpha_1 dt + \sigma_1 dB_t^{Al} \tag{4.3}$$

$$\frac{dP_t^{Cu}}{P_t^{Cu}} = \alpha_2 dt + \sigma_2 dB_t^{Cu} \tag{4.4}$$

Where (B^{Al}, B^{Cu}) is a two-dimensional Brownian Motion with a correlation coefficient equal to 0. Glass and Silicon are not traded commodities and so, their base prices P_t^{Gl} and P_t^{Si} are adjusted by inflation to reflect an estimation. All costs overtime are also adjusted by inflation. Since the investment decision that the U.S. Government is evaluating is long-term, their expected total cost Ω_A is determined by the sum of yearly cost under the benchmark case and under the new option after the investment that they have made:

$$\Omega_A = \mathbb{E}\left[\sum_{t=0}^{\tau_A} \omega_t^{BM} e^{-rt} + I_{\tau_A} e^{-r\tau_A} + \sum_{t=\tau_A}^{T} \omega_t^{A} e^{-rt}\right] \tag{4.5}$$

Where I_{τ_A} is the one-time sunk cost to establish the recycling facility in option A. In equation 4.5, τ_A marks the time of the investment. Formally, τ_A is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark case to the post-investment one[15]. In other words, storage cost

[14]Plastics (Pl) are also recovered during the recycling process, but cannot be directly recycled due to contamination, and generate a cost rather than income.

[15]Let $(\Omega, F, \{F_t\}_{t\in I}, \mathbb{P})$ be a filtered probability space, i.e. a probability space equipped with a filtration of σ-algebras. Then the random variable τ_A is a stopping time if $\{\omega \in \Omega : \tau(\omega) \leq t\} \in F_t$,

or BM is incurred as long as the recycling plant is not installed, but once it does the one-time investment cost I_{τ_A} to install the plant is triggered and the cost of recycling, or $Option\ A$, substitute those of BM. The U.S. Government will decide when to invest in $Option\ A$ by minimizing their total expected sum of future discounted cost:

$$\min_{\tau_A} \Omega_A \tag{4.6}$$

4.3.3 Option B

Considering that a centralized location could also not be optimal to solve this issue, we allow the model for an alternative to installing two regional facilities to distribute the recycling $Option\ B$. For example, one in the west coast and the other in the east coast provided that a great number of panels are allocated in those states. Under this option, a facility is installed as long as excess investment is less than potential savings from logistics $\kappa_t^{tr}(Q_t, \Phi, B)$ that result from the distribution of the operation regionally. Now there could be up to two recycling facilities, each facility would deal with the whole volume of scrap PV panels generated for its corresponding region, and their yearly cost ω_t^B could be described by:

$$\begin{aligned} \omega_t^B = &+\kappa_t^p(Q_t^1, B) + \kappa_t^m \gamma^{Pl}(Q_t^1, B) + \kappa_t^{tr}(Q_t^1, \Phi, B) \\ -P_t^{Al}\gamma^{Al}(Q_t^1, B) - P_t^{Cu}\gamma^{Cu}(Q_t^1, B) - &P_t^{Gl}\gamma^{Gl}(Q_t^1, B) - P_t^{Si}\gamma^{Si}(Q_t^1, B) \\ &+\kappa_t^p(Q_t^2, B) + \kappa_t^m \gamma^{Pl}(Q_t^2, B) + \kappa_t^{tr}(Q_t^2, \Phi, B) \\ -P_t^{Al}\gamma^{Al}(Q_t^2, B) - P_t^{Cu}\gamma^{Cu}(Q_t^2, B) - &P_t^{Gl}\gamma^{Gl}(Q_t^2, B) - P_t^{Si}\gamma^{Si}(Q_t^2, B) \end{aligned} \tag{4.7}$$

Where Q_t^1 includes only the panels for the western states: Arizona, California, Colorado, and Utah. While Q_t^2 includes only the panels the eastern states, Massachusetts, and New York. The rest of the panels for states not listed above are distributed evenly between the two regions.

As it can be observed, two simultaneous options similar to $Option\ A$ are considered in this setting. Once again, the government is evaluating the option to undertake a long-term investment in the future. Their expected total cost Ω_B is determined by the sum of yearly cost under the benchmark case and under the new option after the investment that they have made.

i.e. the decision to stop waiting and to invest is only based on historical data.

$$\Omega_B = \mathbb{E}\left[\sum_{t=0}^{\tau_B} \omega_t^{BM} e^{-rt} + I_{\tau_B} e^{-r\tau_B} + \sum_{t=\tau_B}^{T} \omega_t^{B} e^{-rt}\right] \tag{4.8}$$

Where $I_{\tau_B} > I_{\tau_A}$ to denote the redundancies and cost insufficiencies that could result from having two recycling plants running simultaneously.

The U.S. Government will decide when to invest in $Option\ B$ by minimizing their total expected sum of future discounted cost. In equation 4.8. τ_B is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark regime to the post-investment one in $Option\ B$:

$$\min_{\tau_B} \Omega_B \tag{4.9}$$

4.3.4 Option C

We can also consider a further option, where another existing facility, originally purposed to recycle other consumer electronics could be adapted to process PV panels as well. This alternative, presented in equation 4.10 and further denoted as $Option\ C$ assumes a similar profit structure as the one presented in $Option\ A$, but adjusts the cost levels to a parameter λ_C, in order to account for potential efficiencies and cost savings in the recycling process. This one facility would deal again with the whole volume of scrap PV panels generated nationwide and their yearly cost ω_t^C could be described by:

$$\begin{aligned} \omega_t^C &= \lambda_C \kappa_t^p(Q_t, C) + \kappa_t^m \gamma^{Pl}(Q_t, C) + \kappa_t^{tr}(Q_t, \Phi, C) \\ -P_t^{Al}\gamma^{Al}(Q_t, C) &- P_t^{Cu}\gamma^{Cu}(Q_t, C) - P_t^{Gl}\gamma^{Gl}(Q_t, C) - P_t^{Si}\gamma^{Si}(Q_t, C) \end{aligned} \tag{4.10}$$

Where $\lambda_C < 1$

Since the U.S. Government is evaluating the option to undertake a long-term investment in the future, their expected total cost Ω_C is determined by the sum of yearly cost under the benchmark and under the new option after the investment that they have made:

$$\Omega_C = \mathbb{E}\left[\sum_{t=0}^{\tau_C} \omega_t^{BM} e^{-rt} + I_{\tau_C} e^{-r\tau_C} + \sum_{t=\tau_C}^{T} \omega_t^{C} e^{-rt}\right] \tag{4.11}$$

The U.S. Government will decide when to invest in *Option C* by minimizing their total expected sum of future discounted cost. In equation 4.11. τ_C is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark regime to the post-investment one in *Option C*:

$$\min_{\tau_C} \Omega_C \tag{4.12}$$

4.3.5 Option D

We also propose a modification of *Option C* where we consider further that cost efficiency could be obtained by installing a recycling plant in Mexico. This alternative, further denoted as *Option D* assumes a similar setting for the one proposed in *Option C*. This potential cost-saving tries to denote that investment and costs could even consider the use of recycling facilities in Mexico that geographically are convenient for southern states, i.e. California, but represent considerable financial efficiencies for this model in practical terms. However, in this setting we account the distance between Mexico and California, and add it up to any other travel distance in between states, i.e. $\Phi^{MX} = \Phi^{CA} + 700$, to establish the additional logistical cost to incorporate a hypothetical recycling plant in Mexico, located some 700 kilometers south of California.[16] Similar to *Option C* we still account for potential cost-savings in operation, now defined by λ_D and their yearly cost ω_t^D could be described by:

$$\begin{aligned} \omega_t^D &= \lambda_D \kappa_t^p(Q_t, D) + \kappa_t^m \gamma^{Pl}(Q_t, D) + \kappa_t^{tr}(Q, \Phi^{MX}, D) \\ -P_t^{Al}\gamma^{Al}(Q_t, D) &- P_t^{Cu}\gamma^{Cu}(Q_t, D) - P_t^{Gl}\gamma^{Gl}(Q_t, D) - P_t^{Si}\gamma^{Si}(Q_t, D) \end{aligned} \tag{4.13}$$

Where $\lambda_D < 1$

Also, the government is evaluating the option to undertake a long-term investment in the future. Their expected total cost Ω_D is determined by the sum of yearly cost under the benchmark case and under the new option after the investment that they have made.

[16]The actual distance to travel from Los Angeles, California to Mexicali, Mexico is close to 700 km.

$$\Omega_D = \mathbb{E}\left[\sum_{t=0}^{\tau_D} \omega_t^{BM} e^{-rt} + I_{\tau_D} e^{-r\tau_D} + \sum_{t=\tau_D}^{T} \omega_t^{D} e^{-rt}\right] \tag{4.14}$$

The U.S. Government will decide when to invest in $Option\ D$ by minimizing their total expected sum of future discounted cost. In equation 4.14. τ_D is a stopping time, or the anticipated optimal investment date whereby the U.S. Government moves from the benchmark regime to the post-investment one in $Option\ D$:

$$\min_{\tau_D} \Omega_D \tag{4.15}$$

4.4 Model Calibration

The case study considered in this work is one of a typical rational investor, in this case, the U.S. government. They want to tackle their problem by recycling all solar PV scrap, while minimizing their cost. The investor is looking to minimize their expenses by setting up one or more recycling centers for PV panels nationwide. The detail on parameters used for the model calibration can be found in Table 4.3 below:

Table 4.3: Model calibration parameters.

Parameter	Explanation	Value	Units	Sources
P^{Al}; P^{Cu}	Price of materials	Stochastic	USD	IndexMundy (2019)
γ	Yield of recovered materials	$\gamma^{Al}=175$; $\gamma^{Gl}=7.8$; $\gamma^{Cu}=638.26$; $\gamma^{Si}=24.65$	kg/ton	DAdamo et al. (2017)
κ_0^p	Unitary recycling cost	\$441.24	USD	DAdamo et al. (2017)
κ_0^m	Unitary cost of conferred materials	\$124.09	USD	DAdamo et al. (2017)
κ_0^{st}	Unitary storage cost	$0.10 \cdot \kappa^p$	USD	–
κ_0^{tr}	Unitary transportation cost	\$0.0050	ton/km	Hooper and Murray (2018)
Q_t	Available supply of panels	See table 4.1	tons	Barbose et al. (2017)
Q'	Installed PV capacity	330,030; 62,284; 400,853	tons	–
I	Investment cost	\$104,751,900	USD	DAdamo et al. (2017)
r	Discount rate	3%	–	–
t	Investment horizon	[2024; 2042]	–	–

As it can be observed, some of the parameters related to the recycling process come from DAdamo et al. (2017). This work was very useful to determine the general costs and expected outputs of the recycling process in our assumptions. The price of materials, supply of panels and transportation cost were obtained from specialized datasets, namely IndexMundy (2019); Hooper and Murray (2018); Barbose et al. (2017). These sources provided detailed historical data that was very valuable to determine some of the main inputs of this model. Finally, storage cost was determined as a general proportion of processing cost, while installed capacity, discount rate and investment horizon were determined based on available data as explained in section 4.3 above.

4.5 Results

This section presents the results for our model. Our initial aim was to determine the optimal time to invest in this effort in order to deal with this issue for the period 2024 to 2042. As it will be described, all options aim to minimize the expected expense of the U.S. Government, who would have the option to delay the investment as long they are willing to pay for the storage cost of the panels generated every period. The analysis also focuses on determining the best state to localize the recycling facilities in each case, considering that the panels are already installed in specific locations, and transportation costs are determined as explained above. Finally, we also sensitize the results by varying important model parameters, in particular, investment and cost, and movements in commodities prices.

4.5.1 First Option

The first option is to invest in one national centralized facility. This sort of effort would require that plant to deal with as many panels as necessary to recycle all of them. We can simply observe that the maximum amount of panels scrap expected to be produced in a single year is 432,550 tons in 2041, would be a good reference, however, when running the model with this setting, we obtain a very inefficient outcome due to idle overcapacity for several periods. In our setting recycling after the maximum capacity required can be distributed between the period that it generates and the following periods, as long as capacity is still available for the current operation. We can then estimate that 330,030 tons of PV panels per year is a more reasonable level of installed capacity to deal busiest operation period for $Option\ A$. With that level of installed capacity, the investment in the recycling facility can be delayed up to 2036 (14 years).

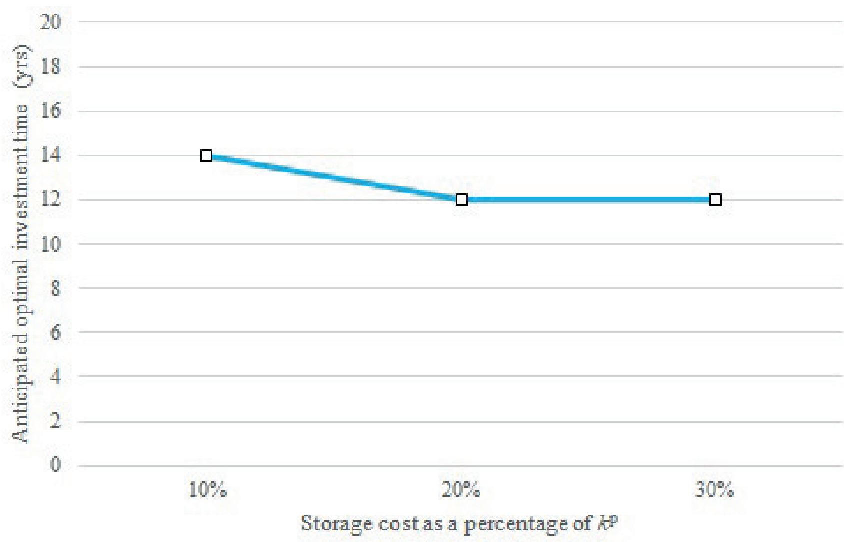

Figure 1. Option A for 330,030 tons of Installed capacity

As we can observe, an increased cost of storage results in an expected faster investment, this as a result of the increased cost that it implies for the overall operation. The reason for this is that storage cost is an imporant parameter for the BM case. As long as we do not invest in $Option\ A$ storage cost is incurred, and so the higher this cost, the more incentive there is to triger the investment.

Based on our setting we can also determine that the best locations to install a single recycling plant according to transportation cost efficiency would be:

Table 4.4: Order of priority to install a single recycling plant according to state location and transportation cost.

Order	State
1	Arizona
2	Colorado
3	Utah
4	California
5	New York
6	Massachusetts

In this table, we can see that Arizona is the best location for a sigle recycling plant, followed by Colorado, Utah, California, New York and finally Massachussetts. This can be determined by comparing the total expected sum of discounted costs to operate the recycling plant in each of those locations.

4.5.2 Second Option

The second option is to invest in two regional recycling facilities, i.e. one on the east and the other on the west coast of the United States. As it can be observed in Appendix B, the longest distance in between states results from Massachusetts and New York to the rest. However, both states are 327.5 Km away from each other, and so setting a recycling plant to serve both states, and another on the west to serve the rest of states, seems to be the best strategy to minimize cost. This allocation could potentially reduce the transportation cost significantly when compared to the best alternative of $Option\ A$. Under this new setting, each recycling facility would have to deal with a recycling volume of 62,284 (east coast) and 400,853 (west coast) tons of PV panels yearly at their busiest operation periods, assuming each one of them also take half of the panels generated by other states. This amount depends on the maximum required capacity or each region and would determine the installed capacity in each case, but we can also optimize the installed capacity for the west coast to allow for the recycling to be distributed over the last 5 years and still allow for all panels to be recycled. Based on our setting we can also determine that the best locations to install two recycling plants according to cost efficiency would be the following:

Table 4.5: Order of priority to install two recycling plants according to the state and transportation cost.

Order	State
1	Arizona & Massachusetts
2	Arizona & New York
3	California & Massachusetts
4	California & New York
5	Colorado & Massachusetts
6	Colorado & Massachusetts
7	Utah & Massachusetts
8	Utah & New York

This option could allow for the facility on the west coast to delay its investment even more, until 2036 (year 16) and the one on the west coast to keep the delay until 2034 (year 14). In any case, the cost of this scenario would be approximately 5.4% more expensive than the best scenario in $Option\ A$.

4.5.3 Third Option

In the third option, we consider the potential of economies of scale by recycling the panels in existing recycling facilities that deal with other consumer electronics. This is a similar approach to the one currently conducted by the European Union. Provided that the operational cost of the recycling process seems to be high enough to exceed potential revenues, the third option considers the possibility to reduce the operational cost even to a point that it could become profitable. In this setting, we take the benchmark case and apply different levels of cost reduction to anticipate the optimal investment date.

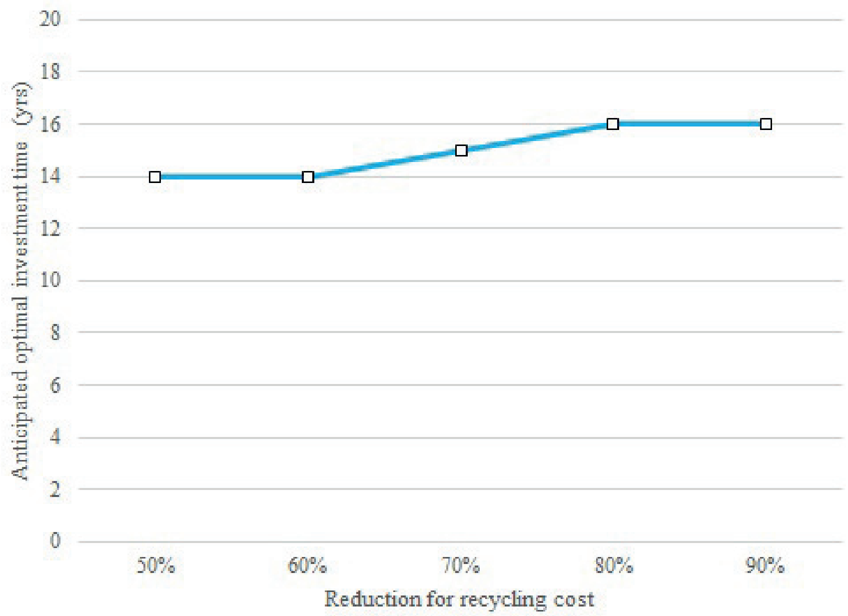

Figure 2. Option C for different levels of reduction for recycling cost.

After running different combinations of cost reduction, we determined that even aggressive cost reductions would not delay the investment. We observe that by reducing the recycling cost anywhere up to 60% we keep the anticipated optimal investment date at 14 years. However if we expect to reduce the cost even more, the anticipated optimal investment date starts to increase, and we can further delay the investment time to 15 years for a reduction of 70%, and to 16 years after a reduction of 80%.

4.5.4 Fourth Option

Similar to the previous option, it is possible to consider a further variation of $Option$ C that would allow the establishment of a single recycling plant in Mexico. In which case, the logistical cost would have to be adjusted accordingly.

Again the delay on the investment could reach 14 years, and we observe that there is no significant difference between the results of $Option\ C$ and D. In fact, the small difference in the results from both options comes from the increased transportation cost needed to take the panels to Mexico,[17] i.e. to transport the panels 700 km more.

4.5.5 Comparison of options

In order to better asses the findings of our study, we set a comparison of the total expected sum of future discounted cost of recycling the panels. We define the comparison as a percentage of cost reduction to the benchmark case, or to delay the investment on any of the options as much as possible, as described in table 4.6 below:

Table 4.6: Comparison of expected sums of future discounted costs resulting from the analysis of options.

Option	Description	Cost savings
BM	Delay the recycling as much as possible	–
C	Use existing recycling facilities (with κ^p at 50%)	72.3%
D	Recycling in Mexico (with κ^p at 50%)	71.5%
A	1 new recycling facility	39.7%
B	2 new recycling facilities	36.6%

We can observe that on average, $Option\ C$ to improve existing consumer electronics plants to deal with solar PV scrap, taking advantage of economies of scale, is the single one option that results in the highest cost reduction, 72.3%. Followed by $Option\ D$ to send the panels to be recycled in Mexico in order to take advantage of reduced operational costs with 71.5% cost reduction, $Option\ A$ to install one recycling plant that deals with all national solar PV scrap represents a cost reduction of 39.7% and $Option\ B$ to install two regional facilities in order to distribute the recycling between them with 36.6% cost reduction. These results only compare for the expected

[17] This analysis does not account for import duties, quotas or other fees that could result from the shipment of panels into a foreign country, but we could expect additional cost resulting from it could be caused.

sums of future discounted costs between options, but do not consider additional complexities, such as the practicality of achieving such increased cost efficiencies or market and political constraints of implementation.

4.5.6 Further options

Besides the results shown in this work, further applications of this model could be developed. i.e. to assess the accelerated decommissioning of panels due to the potential efficiency increases resulting from the development of new technologies. In addition to that, the period between 2024 and 2042, included in the present analysis poses an interesting case that could allow for a diversity of potential solutions due to the increased volume of PV panel scrap to be generated.

Assuming scalability would prevent financial losses from the recycling process, and different levels of cost reduction could result in the immediate implementation of the first recycling plant as soon as the critical volume of scrap material is reached. Other alternatives to accelerate implementation and minimize cost by increasing profitability could include:

1. Recycling thin-film panels together with crystalline Silicon panels, to extract more valuable metals from the process, in order to increase potential revenue.

2. Innovate the recycling process in order to reduce operational cost and/or increase valuable recovered materials (similar to $Option\ C$ and D above).

4.6 Conclusion

Regardless of the potential environmental benefits of crystalline Silicon panels recycling outlined in this work, solar PV panel recycling still represents an important challenge financially, operationally, technically and logistically. As we were able to show with our model, the cost and income structure proposed by DAdamo et al. (2017) results in financial losses and could ultimately result in improper handling of the panels. As a step forward of previous research, our approach implements a more realistic market price estimations for Commodity Prices (Copper and Aluminum) and estimates the availability of the panels for recycling based on real market data. We also sensitize for potential cost efficiencies. Although the location of the panels is known and most of them are concentrated in only 6 states nationwide, the panels are still heavy and complicated to handle and the exact time of deployment is still uncertain.

As challenging as it may seem, some components of the PV panels require proper management after the end of their useful life. They have to be properly handled, and we better find the most efficient and effective way to do so. The environmental risk resulting from improper management would just be too high to leave it unattended. In addition of establishing that potential environmental risk, there are important policy issues to solve in order to deal with this situation:

1. Regulation needs to be developed and implemented to establish guidelines for proper management of PV panels after deployment in the United States, and subsidies could be an important part of it.

2. Since the cost structure of recycling for silicon panels seems to be too expensive, subsidies are required to trigger seed investments, and the amounts required under different scenarios seem to be reasonable, as described by this work. This could allow for private investments to be started.

3. Besides subsidies, other market mechanisms, i.e. direct payments could be implemented to reduce the burden of cost on the U.S. Government. Some countries in Europe already have such schemes in place to deal with recycling of electronics.

4. Waste management and recycling infrastructure will need to be developed accordingly. Early action results in less expensive implementation.

Different options allow for more efficient investment in the recycling plants, as shown in section 4.5 of this work. Current regulation regarding this issue fails short to address this problem properly, even in the states with the majority of panels, where the issue has been identified by authorities and initial efforts have been done. In any case, it seems that it could still be optimal to slightly delay the implementation, depending on the alternative chosen, as far as storage cost keeps low. In any case, recycling capacity will need to be developed to deal with the expected scrap material to be generated over the next decades, since traditional waste dumping off the panels is not an option, provided the environmental risk that it poses. The best alternative would be to locate a single recycling facility in Arizona, provided cost savings can be achieved, but other alternatives also pose interesting opportunities. This paper proposes several potential solutions to this problem, and many more could also be considered. Dealing with solar PV panels at the end of their useful life will be, in any case, a very costly endeavor and so early action could result in better alternatives for the authorities.

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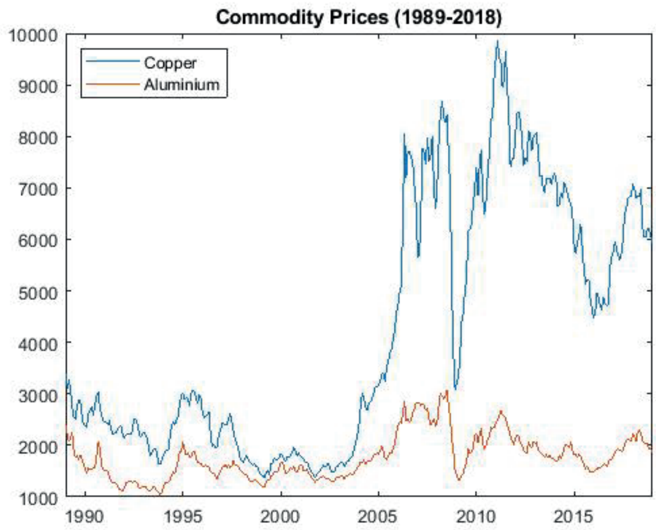
Appendix

Commodity prices 1989 - 2018 (in USD)



Source: Based on data from IndexMundy (2019)

Distance between states (in Km)

Km	Arizona	California	Colorado	Massachusetts	New York	Utah
Arizona	0					
California	1183.2	0				
Colorado	772.0	1229.0	0			
Massachusetts	4098.7	4979.6	2883.0	0		
New York	3751.2	4688.2	2688.0	327.5	0	
Utah	889.1	1243.1	457.0	3842.2	3550.6	0

Source: Based on data from Google Maps, 02.05.2019

Part III

Curriculum Vitae

Curriculum Vitae

Personal Details

Name:	Carlos Alberto Vargas
Date of birth:	October 1, 1980
Nationality:	USA and Mexican

Education

September 2016 - September 2019	Doctoral Program at the University of Zurich, Department of Banking and Finance, Lehrstuhl Prof. Dr. Marc Chesney (Switzerland)
September 2011 - March 2013	Master of Liberal Arts in Sustainability and Environmental Management at Harvard University (USA)
September 2004 - June 2006	Master of Business Administration at Instituto Panamericano de Alta Dirección de Empresas (Mexico)
August 1999 - May 2003	Bachelor of Arts in Finance at Instituto Tecnológico y de Estudios Superiores de Monterrey, Campus Guadalajara (Mexico)

Professional experience

Since 2013	Lecturer for Sustainable Finance and Investments at Harvard University Extension and Summer Schools (USA)
2014 - 2016	Chief Financial Officer at New Evolution Ventures (Mexico)
2012 - 2013	Chief Operating Officer at The Vertex Companies (USA)
2007 - 2011	Senior Investments Associate at BBVA Bancomer (Mexico)
2006 - 2007	Real Estate Investments Manager at Liverpool (Mexico)
2003 - 2004	Financial Analyst at Hewlett Packard (Mexico)